

D. Project Description

D.1 Introduction and Motivation

Complex-terrain meteorology spans numerous application areas, including wind energy harvesting (Banta et al. 2013), air pollution in urban basins (Fernando & Weil 2010), aviation (Politovich et al. 2011), Alpine warfare (Winters et al. 2001), and firefighting (Holden & Jolly 2011). Of particular importance is the planetary boundary layer (PBL) where most of the anthropogenic activities take place and topographic processes pronouncedly alter the flow. Winds in complex topography (mountainous terrain) embody much wider space-time scales than on flat terrain, wherein non-linearity of the flow is more pronounced and the predictability more difficult. The state-of-the-science of mountain meteorology has been reviewed by Fernando (2010) and in a series of papers in Chow et al. (2013), complementing earlier excellent monographs of Blumen (1990), Baines (1998) and Whiteman (2000). Unlike the canonical flat terrain boundary layer, where large-scale pressure (synoptic effects) and thermal gradients drive the flow, the complex terrain PBL ingrains the additional influence of slope and valley flows (thermal circulation) due to heating and cooling of the ground over the diurnal cycle (Fernando et al. 2001).

Typically, the frequency content of wind variability in complex terrain peaks at synoptic scales, but a secondary peak also appears in the wind spectrum at ~ 12 hour periods where the thermal circulation reverses from daytime upslope (anabatic) and upvalley flow to nighttime downslope (katabatic) and downvalley flow, and vice versa. During the daytime intense convection period, variability at the scales of tens of meters and minutes is significant, representing the scales of convection cells (Kaimal & Finnigan 1994). Superimposed therein is the turbulence produced by shear and thermal forcing in the atmospheric surface layer. While quiescent, low-synoptic periods are important in air pollution studies, and hence have been a topic of intense study (Zardi & Whiteman 2013), energetic synoptic conditions with high frequency content are of great interest in other application areas. Characteristics of such flows include high turbulence levels due to shear layers, flow separation from topography (Helmis et al. 1995), presence of dividing streamlines (Hunt 1980), gustiness, flow-flow and flow-topography collisions (Retallack et al. 2006), and flow meandering and intense low-level jets (Banta et al. 2002). Ensuing unsteady effects are unwelcomed in wind turbine siting, aviation and forest fire control. For example, ‘gustiness’ of winds (expressed by the gust factor, or the ratio of gust wind speed to hourly mean wind speed) is closely related to turbulence, and it is a critical design parameter specifying the mechanical lifetime of wind turbines (Fragoulis 1997; Wieringa 1973). One of the greatest challenges of wind energy vis-à-vis conventionally generated electricity is the dependence of former on the ‘volatility’ of winds (Giebel 2011), particularly on two time scale windows, one determining turbine control (from milliseconds to tens of seconds) and the other on the integration of wind power to the electric grid (minutes to weeks). Both of these windows need attention, as scales of several minutes or less are not usually monitored and are less predictable.

This proposal alludes to a unique and unprecedented opportunity to study complex terrain flows at the microscale (seconds to hours in time and up to a few hundred meters in space) by participating in a European project to develop a wind atlas for Europe, a component of which calls for fundamental scientific research. The long term goal of the overall project is to provide improved capabilities for wind energy prospecting (in Europe), and the present proposal concerns the participation of US groups to study flow regimes and scales that have received little attention hitherto - microscale mountain meteorology. The energy cascading through mesoscales is also of interest.

In addition to knowledge creation, the proposed work will provide a platform for improvement of wind energy prospecting. Wind energy is recognized to be a clean, renewable energy source that can reduce the dependence on fossil fuels, which are not only facing depletion but also at the center of climate change debate (Leung & Yang 2013). According to the latest Global Wind Report (GWEC 2014), the total global wind power installation at the end of 2013 was 318 GW. It is growing at a rate of about 20% (Sørensen 2011), with different nations taking the lead at different times. Germany led wind energy production until 2007, with the US surging ahead in 2008, to be overtaken by China in 2010 (Premalatha et al. 2014). Wind resource characterization is central to all aspects of wind energy production, from identification of suitable

sites to assessment of economic viability of wind farms to the design and management of wind turbines (Schreck et al. 2008; McElroy et al. 2009; Shaw et al. 2009; Sørensen 2011). The energy available in the winds varies as the cube of wind speed, and hence the variability of wind speed, both in space and time and over a range of scales, critically affects energy harvesting. Various empirical and semi-empirical formulae exist to predict wind variability based on the site and time of the day, which provide operational guidance (EDSU 1985; Walmsley et al. 1989; Mann 1994, 1998; IEC 2005; Woebbecking 2007). The prediction of high frequency wind variability in complex terrain, nevertheless, has been a vexing challenge for PBL studies, let alone in wind engineering (Burton et al. 2011).

Wind resources are sensitively determined by local scales, and hence by physical geography such as land use and land cover and topographic features that modify not only the synoptic influence but also local turbulence (Singh et al. 2006; Clifton et al. 2013). Winds on top of the hills are much stronger than in the lee side of the hills, and on the scale of a wind turbine, nearby obstacles and local vegetation also matter (Burton et al. 2011). It is at this microscale that the predictability of winds is poor and the variability is random. In fact, for many areas of economic interest, the wind climatology has been already mapped using mesoscale models and assimilated meteorological data, nonetheless, the predictions of available wind energy to turbines have been stymied by errors introduced by space-time variability at small scales (Palma et al. 2008; Liu et al. 2011; Mahoney et al. 2012; Delle Monache et al. 2013; Carvalho et al. 2014). Accurate wind forecasting is also crucial for power optimization (Lei et al. 2009), environmental impact assessment (Dai et al. 2015), and load balancing (Giebel 2011).

Earlier investigations on complex terrain meteorology have focused largely on quiescent periods, with application to air pollution. Conversely, studies with synoptic influence have been centered on the linear theory for neutrally stratified flow by Jackson & Hunt (1975) and Hunt et al. (1988) for low slopes ($\leq 17^\circ$; Walmsley & Taylor 1996), with wind energy and dispersion applications (Belcher & Hunt 1998). Erstwhile field works have concerned flow over escarpments (Jensen & Peterson 1978), terrain with inhomogeneous roughness (Sacré 1979) and low slopes with wind turbines (Högström et al. 1988; Helmis et al. 1995). The significant role that turbines play in adjusting heat, mass and momentum exchanges in the surface layer is now well documented, but lacks detailed understanding (Zhou et al. 2012; Rajewski et al. 2014). Jackson & Hunt's (1975) work has been extended to three-dimensional flow by Mason & Sykes (1979). Nonetheless, linear theories have been the backbone of many commercial numerical codes, for example, MS3DJH, MSFD, WAsP and ADMS (Taylor et al. 1983; Walmsley et al. 1986; Troen et al. 1989; Carruthers 2007; Carruthers et al. 2011; Heist et al. 2013).

Recent work has clearly pointed to the importance of microscale modeling of complex terrain flows in wind energy applications (Palma et al. 2008; Liu et al. 2011; Carvalho et al. 2014) by illustrating that errors in using mesoscale models for wind prospecting can reach 100%! In recognition, the European Union (EU) has recently granted a ~€13M megaproject under the sixth framework ERANET+ -- a program that requires financial contributions from at least six EU nations, with the European Commission contributing one third of the total. The successful project of our European partners, ERANET+: New European Wind Atlas (NEWA), is contributed by a consortium of eight countries (Section J) to develop a data bank of European wind climate. The NEWA outcomes will include an EU wind climate database and provide hourly variables at each grid point (with accuracy over 10%). Through a combination of measurements and modeling, it will produce maps of wind data at several heights and at horizontal resolution down to 100 meters, covering EU member states and their exclusive economic zones. Existing models will be improved as well as coupling thereof ("model chain"). Uncertainty estimates for models and model chains will be published. Analysis will be performed for short-term forecasting predictability.

The NEWA will also have information on regional wind resource assessment, wind variability and local siting of turbines - including guidelines and computational procedures for the effects of shelter from buildings and other obstacles, effects of varying surface roughness and for the influence of hills and mountains on the wind climate and wind power resources. The goal is to reduce the AEP (Annual Energy Production) estimation error from the current level of 40-50% to 3-10%. The consortium coordinator is Dr.

Eric Björklund (Danish Energy Authority, DEA), and the Principal Investigator is Professor Jakob Mann (Technical University of Denmark, DTU). The project start date is May 01, 2015, and deliverables include an electronic Atlas, dynamical downscaling methodologies and open source models validated through previous as well as new field data.

The most noted existing dataset on synoptic flow over a hill is based on the Askervein Hill field experiment (Taylor & Teunissen 1983), and the ERANET+ database is expected to be a significant augmentation of Askervein. There will be several field campaigns over the project period of five years, in mountains (see below), forested hills (Kassel in Germany), offshore (northern Europe), large changes in surface characteristics (Alaiz mountain, Spain) and cold climates (high altitude ridges in Turkey). The mountain-terrain field study within ERANET+ is to be conducted in 2016-2017 in central Portugal, within the Vale do Cozadeiro near the town of Perdigo, located northeast of Porto. Given the closeness to its namesake city, the campaign has been dubbed Perdigo (Portuguese for “Partridge”).

The US investigators led by the PIs have been invited to participate in the Perdigo campaign, with their own science plans and financial resources. A preliminary meeting with Europeans was held in July 2013, followed by a Scientific Program Overview (SPO) and Experimental Design Overview (EDO) proposals to NSF in January 2014, which were declined due to programmatic reasons (Section D.4, Table 2). The NSF reviews were affirmatively positive. During September 4-6, a visit to the Perdigo experimental site by the PIs and Dr. Steve Oncley was funded by Fundação Luso-Americana para o Desenvolvimento (FLAD). Given their interest in participating in Perdigo, the US Army Research Office (ARO) funded a workshop at University of Notre Dame during September 25-26, 2014, on “Microscale Modeling of Complex Terrain Flows” with focus on Perdigo science plans, instrumentation and logistics. Armed with robust science plans and certainty of the status of the EU Project, the US team is now in a sound position to seek participation in Perdigo experiment, and hence this revised proposal. This proposal seeks to formalize US participation in Perdigo, undergirded by NCAR/EOL facilities. Funding is requested for travel to a workshop at a location near Perdigo, followed by a site visit, as well as for domestic planning meetings.

D.2 Current State of Knowledge

During February 1-2, 2010, with the support of Army Research Office, a meeting was hosted by the PI Fernando in Tempe, Arizona to identify critical scientific barriers for weather prediction in mountainous terrain, which led to the development of the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program (2011-2016), a Multidisciplinary University Research Initiative (MURI) of the Office of Naval Research (www.nd.edu/~dynamics/materhorn). Three large field experiments have already been completed under this program (Fernando & Pardyjak 2013; Fernando et al. 2015), the data of which are being analyzed by numerous groups. In designing the experiments, the knowledge gained from prior studies was evaluated so that the new data can address overarching current issues. The complexity of mountain-terrain flows and programmatic constraints, however, required MATERHORN to be narrowed down to a particular set of problems – mesoscale processes and modeling. The microscales were not addressed, although their practical importance was emphasized. To this end, Perdigo offers a sophisticated research platform, and underlying critical science issues are identified in Section D.3. A brief review of multi-scale processes in complex terrain meteorology is provided below.

Figure 1 summarizes various flow and boundary-layer types in a valley located between two long (normal to the paper) mountains that disturb the flow in free atmosphere. The figure was drawn based on the reviews of Blumen (1990), Whiteman (2000), Fernando (2010), and Chow et al. (2013) and knowledge gained from recent complex-terrain field campaigns (e.g., Doran et al. 2002; Grubisic et al. 2008; Politovich et al. 2011; Price et al. 2011; Fernando & Pardyjak 2013; Fernando et al. 2013). The scales are denoted according to the classification of Orlandi (1975). Mountains of height less than 600 m are typically defined as hills (Barry 2008). When the approach flow is stably stratified at night (in blue), the wake of the leading mountain consists of lee waves, rotors and separated vortices and coherent structures penetrating in to the

valley carrying momentum, whilst under weak synoptic conditions a downslope (katabatic) flow defines a shallow *mountain atmosphere*. Convergence of downslope (V_{ds}) flows in the valley forms a stably stratified cold pool, signifying the *valley atmosphere*, which in this case encompasses the *stable boundary layer* near the ground. The combined influence of mountain wakes and valley spreads to the *mountain-valley atmosphere*, which transitions to free air through a layer signified by perturbed (synoptic) flow by the mountains. The disturbed layer by the mountains and valley collectively defines the *complex terrain atmospheric boundary layer*. Depending on the terrain and variability of the land cover, different microclimates are possible. Conversely, during daytime convection (in red), a convective boundary layer develops deep, and the upslope flow (V_{us}) and its separation and formation of cumulus clouds are typical features under weak synoptic conditions. The separation of synoptic flow at the ridge sheds energetic vortices into the mountain-valley atmosphere, creating unsteady flow.

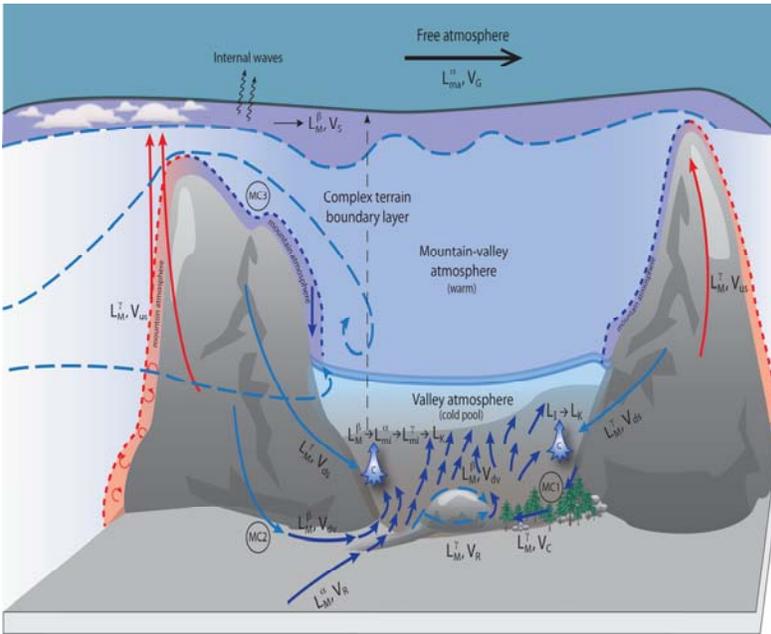


Figure 1: Atmosphere in complex terrain. (L_{Ma}^{α}, V_G) – macro- α ($>10^4$ km), global; (L_M^{β}, V_S) – macro- β ($(2-10) \times 10^3$ km) synoptic; (L_M^{α}, V_{dv}) – meso- α – $(2-20) \times 10^2$ km regional downvalley; (L_M^{β}, V_{dv}) – meso- β ($(2-20) \times 10$ km, local down valley; (L_M^{γ}, V_{ds}) – meso- γ (2-20) km, local downslope or locally distorted regional (R)/canopy (C) flow; (L_{mi}^{α}, V_{dv}) – micro- α (0.2-2) km, local flow interactions and collisions; (L_{Mi}^{β}, V_{dv}) – micro- β (20-200) m, instabilities; (L_{Mi}^{γ}, V_T) – micro- γ (<20 m), turbulence and eddies down to Kolmogorov scales L_K . MC – microclimates

As mentioned, the current understanding of mean flow past hills is mainly grounded on the works of Jackson & Hunt (1975), Hunt et al. (1988) and extensions. The theory applies to neutrally stratified flow over low hills, and formally assumes small perturbations to the approach flow caused by a hill. The outer layer is assumed inviscid, and turbulent transport processes are dynamically significant only within an ‘inner layer’ theoretically determined by the roughness height z_o and characteristic mountain width L , irrespective of the mountain height h . The assumptions leading to linearized equations of Jackson & Hunt (1975) are sometimes unheeded in applications, for which justifications are provided based on scaling and dynamical arguments (Hunt 1980; Britter et al. 1981; Mason & King 1985).

Taylor et al. (1987) reviewed ‘low hill’ experiments, and classified them based on key variables in the framework of Jackson & Hunt (1975). The emphasis was on the mean profiles of streamwise velocity and turbulence intensity, whereas insights gained on the modification of turbulence structures by orography were sparse. Figure 2 extends the Taylor et al. (1987) diagram to include more recent studies relevant to the Perdigão (double hill) experiment, some of which are listed in Table 1 (experiments without emphasis on synoptic effects are omitted for brevity). Some studies have suggested that winds upstream can be predicted using a composite ‘regional roughness length’ based on the topography and the surface roughness (Tieleman 1992). At the heights of importance to wind turbines, the flow can be treated as ‘rapidly distorted’ as in Jackson & Hunt (1975), in that the variation of mean winds occurs more rapidly than that of turbulent intensity. Thus, the effect of hills can be treated as irrotational fluctuations caused by the distortion of mean flow by the hill, and hence the normalized turbulence intensity decreases as flow accelerates past a hill

(Schlez 2000). Although such assumptions appear intuitive, the processes associated with flow distortions are not that straightforward and involve intercomponent energy transfer from the longitudinal to the lateral components and corresponding shifts in the spectrum (Petersen et al. 2013).

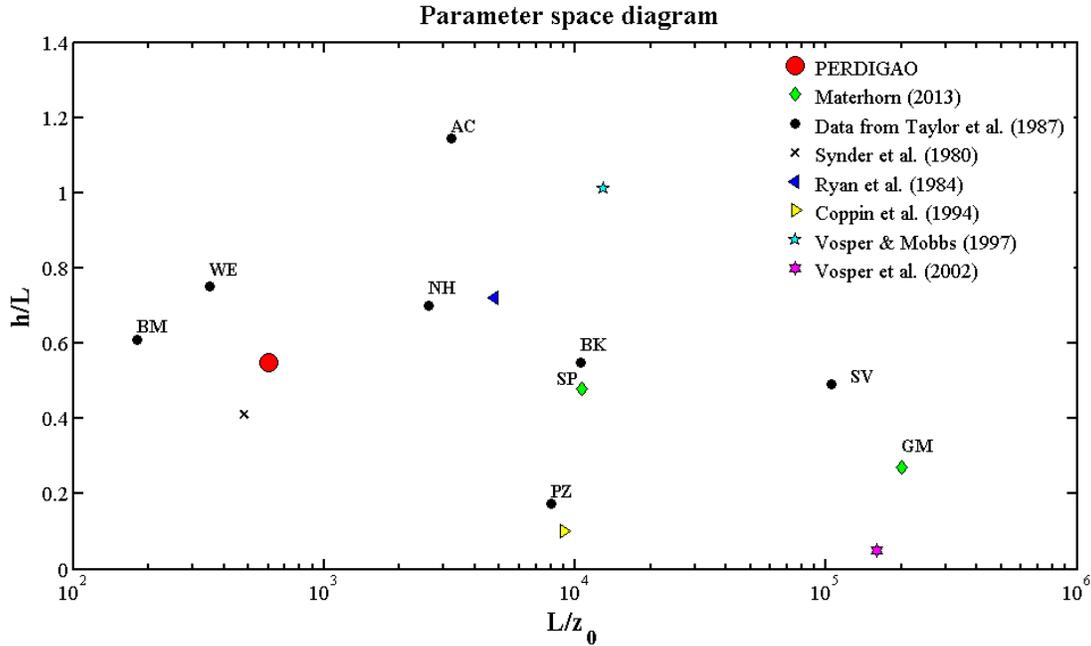


Figure 2: Past field experiments on flow over hills classified according to key parameters, h/L versus L/z_0 . Here h is the height of the hill, L the half width up to $h/2$ and z_0 is the roughness height. The original diagram of Taylor et al. (1987) has been modified to include relevant and recent experiments. From the original paper: BM – Black mountain, WE – Worms Embankment; AC – Ailsa Craig; NH – Nyland Hill; BK – Brent Knoll; PZ – Pouzauges Hill; and SV – Sirhowey Valley. New inclusions: Perdigião, MATERHORN (two sites, Small Peak SP and Granite Mountain GM; Fernando & Pardyjak 2013), hill Tighvein, Isle of Arran (Vosper et al. 2002), Black Combe mountain in Cumbria (Vosper & Mobbs 1997); Cinder Cone Butte, Idaho (Snyder et al. 1980), Coopers Ridge, Australia (Coppin et al. 1994) and Steptoe Butte, Washington (Ryan et al. 1984).

Table 1: Field experiment studies relevant to Perdigião experiment in chronological order (Some are not included in Figure 2 because of the unavailability of accurate parameters). Perdigião is a double hill.

Time-frames	Field Experiments
1979-1986	Brent Knoll, Pouzauges Hill, Black Mountain, Ailsa Craig, Kettles Hill, Askervein Hill, Steptoe Butte, Bungendore Ridge, Sirhowey Valley, Blashaval, Cooper’s Ridge and Nyland Hill
2002-2003	Tighvein, Gaudergrat
2004, 2006	Owens Valley (California, USA), Sierra Rotors Project (SRP), followed by Terrain-induced Rotor Experiment (T-REX)
2007-2008	Bolund Hill (Denmark)
2010	Benakanahalli Hill (Karnataka, India)
2012-2013	MATERHORN (Dugway Proving Grounds, Utah)

Because of strong spatial acceleration of winds in certain areas, complex terrain offers attractive locations for wind turbine siting. Conversely, the bane is the difficulty of wind prediction in such areas, given the space-time variability of the wind field and its sensitivity to non-stationary thermal forcing (Carvalho et al. 2014). Figure 1 depicts the sheer complexity of flow, including flow separation, collisions

between flows, Coandă effect, secondary flows, convergence/divergence, internal and lee waves, roughness effects, unsteadiness, stratification, land use and directional shear. While the previous experimental efforts have contributed immensely to our understanding (Doran et al. 2002; Grubisic et al. 2008), there is a demonstrated need for more high-resolution data at the microscale, in particular for wind energy applications (Lopes et al. 2007; Ayotte et al. 2010; Sullivan et al. 2010; Liu et al. 2011; Churchfield et al. 2012). As discussed below, mesoscale models are grossly insufficient to estimate the AEP in the wind turbine industry, given high spatial gradients in topography and hence in wind fields.

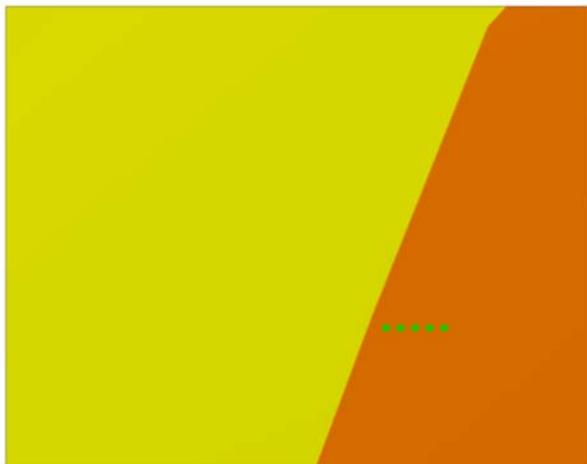


Figure 3a: Mesoscale modeling (5.12 km resolution) output of the wind energy (magnitude in color) for the installation of five 2MW turbines (shown by green dots).

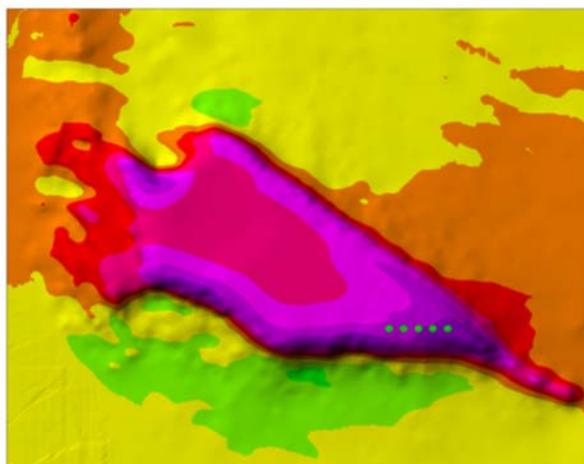


Figure 3b: Same as in (a), but with a microscale model with 20 m resolution nested with the mesoscale model in (a).

Figure 3 illustrates wind calculations for siting of five 2 MW turbines in complex terrain performed using mesoscale and microscale models (Palma et al. 2008). The AEP calculated by the mesoscale modeling is 39 GWh whereas by the microscale modeling is 55 GWh! Such disparity is unacceptable in the design process, emphasizing the importance of information delivery at high resolution. Microscale models, nonetheless, are still nascent and in need of improvements, especially by accounting for stratification, topography and background turbulence. In the wind sector, the practice hitherto has been to extrapolate, using simple (often linearized) models, the tower measurements taken elsewhere in the landscape to identify potential wind turbine locations (Ayotte et al. 2001). Clearly this is not a viable practice in the long haul.

To develop or improve micrometeorological models, the need for high-resolution data cannot be overemphasized (Palma et al. 2008). So far, the field emphasis has been on mesoscale data, for both model validation and process studies (Doran et al. 2002). As mentioned, in the early 1980's one of the most well-known experiments was conducted by an international group of experts at Askervein Hill in the UK, characterized by smooth and low slope ($< 20^\circ$), few irregularities, and uniform roughness (Taylor & Teunissen 1983). The flow was clean, in that flow separation, reattachment and recirculation were absent or only intermittent. The mean flow measurements therein have been used extensively to validate linearized models such as Jackson & Hunt (1975). Linearized models performed well upstream of the hill and not so well downstream, but the project was sufficiently successful (Mann 2000) for developing and validating computationally fast commercial codes for wind resource estimation (Troen et al. 1989; Corbett et al. 2008). Wind tunnel experiments, however, show that linearized models overestimate the wind speeds over the ridge of steep mountains (Ayotte & Hughes 2004). The problem is particularly acute in situations where turbines are on the top of steep ridges with sub-ridges pointing away from the main ridge; they experience extremely large fluctuations in wind speed and direction (Berg et al. 2011). Kindred deficiencies have spurred the development of non-linear models such as Reynolds-averaged Navier-Stokes solvers (RANS) and large-eddy simulations (LES). In all, the Askervein experiment continues to serve well for comparison

with non-linear models (Castro et al. 2003; Lopes et al. 2007; Chow & Street 2009; Golaz et al. 2009; Bechmann & Sørensen 2010; Berg et al. 2011), but comparisons have not been performed at sufficiently high spatial resolution or with data from steep terrain representative of wind farm locations.

D.3 Science Goals

The review of literature and discussions in the recent (Sep. 25-26, 2014) workshop at Notre Dame led to identification of a myriad of research needs. These were prioritized and narrowed down to five science foci based on near-term importance, consistency with the European research agenda and availability of resources. For each focus area, a set of hypotheses were developed and approaches to test them at Perdigo are outlined below. The general experimental plan in D.4 allows investigations on these topics, and suitable augmentation of instrumentation by funded groups is expected (Section I). Modelers will use existing numerical tools and improvements thereof to simulate Perdigo flows at the microscale. Working with observationalists, they will elucidate new physics and help interpret observations. This SPO covers only the Perdigo experiment, whilst numerical studies will be articulated in individual grant proposals.

Experimental foci

1. Multi-scale flow interactions in complex terrain

Hypotheses: Local circulation in the valley represents complex interactions between thermal circulation, regional flow and synoptic forcing, and thus local flow is highly variable in space and time, depending on the strengths of each contributor and interactions thereof. Turbulence and mixing in the valley (and hence eddy coefficients) are also highly variable over a range of scales.

Approach: (a) Characterize synoptic, regional and mesoscales, including forcing such as pressure gradients and sea surface temperature (site is ~ 100 km from the coast), (b) Measure local conditions and their evolution at selected sites (i.e., flow collision, interaction and flow distortion hotspots, identified intuitively or long-term monitoring) at high space-time resolution, including turbulence and fluxes, (c) Identify processes and phenomena - shear instabilities, internal waves, slope flows, flow collisions - at locations in (b) via scanning Lidars, IR imaging, remote and in-situ sensing, and relate their appearance to local conditions (e.g., dimensionless parameters), (d) Delineate physical mechanisms and interactions thereof, identify their space-time variability and parameterize relevant property fluxes, (e) Demarcate appearance of various flow regimes as functions of (suitably scaled) property footprints.

Implications: Strong interactions of synoptic and thermally/mechanically induced flows occur at micro- α or smaller scales (Sturman et al. 2003; Fernando et al. 2015), but their flux footprints are unknown. Careful multi-scale observations are invaluable for improving microscale models (Landberg et al. 2003; Liu et al. 2011).

2. Influence of terrain heterogeneity

Hypotheses: While the assumption of an idealized two-dimensional valley within two parallel ridges, as in Perdigo (Section D.4), is a reasonable first step in modeling, the natural variability of topography and land use can greatly modify the flow within the valley and over the ridges. In particular, the presence of a simple ‘Gap’ in one ridge can generate secondary circulation, jetting, interacting shear layers and cross-slope flows that modify the flow and turbulence over a certain spatial extent – which is determined by the overall topography, topographic anomalies (gaps), approach flow and flow stability.

Approach: (a) Characterize the approach flow, background stability and orography of the gaps, (b) Verify Jackson & Hunt (1975) framework for low slope angles (i.e. $h/L < \sim 0.1$) and no gap areas of the fore mountain at neutral stability, and explain discrepancies, (c) Map 3D velocity and turbulence fields in the vicinity of the gap and away from it at high resolution, identify and explain the differences, (d) Measure the pressure field, local circulation, separated flow, flow structures, secondary circulation and turbulence at selected locations at high space-time resolution, (e) Measure coherent structures at the ridge shear layers and gap-separated flows and estimate related momentum transports, (f) Identify the lengthscales of flow distortions, both vertical and horizontal, at the gap and away from it, (g) Quantify internal wave radiation

under stable conditions and upslope flow separation under unstable conditions at gap area and away from it as a function of flow and stratification parameters, (h) Study how the results of (a)-(f) depend on atmospheric stability (stable, unstable and neutral),

Implications: Topographic inhomogeneities of microscales are known to substantially modify both thermally and synoptically driven flows (Rotach & Zardi 2007), which cannot be captured by mesoscale models. The spatial extent and magnitude of this modification as well as possible unsteady phenomena such as vortex shedding is of importance in wind turbine siting and operations (Fesquet et al. 2009).

3. Transitions and diurnal cycle

Hypotheses: The morning and evening transitions under low synoptic conditions in a nominally two-dimensional narrow valley are different from that on a (idealized) long slope abutting a valley. For long slopes, the evening transition arguably is dominated by front formation, shadow fronts and slab-like flows (Nadeau et al. 2011; Fernando et al. 2013), but in narrow valleys the flow is affected by recirculation cells, valley circulation and solar-insolation asymmetry on mutually facing slopes. The morning transition on a long slope includes intrusion formation, shaving phenomena and flow separation (Princevac & Fernando 2008), but again the case of a narrow valley is dynamically different. The kinetic energy budgets and turbulent mixing during transition also are different from the long slope case. Three-dimensionality introduced by gaps and topographic anomalies are expected to modify the transition mechanism in their vicinity.

Approach: (a) Quantify 3D wind variability with continuous measurements at representative sites with high space-time resolution (Windscanner systems; see Section D.4), (b) Observe surface temperature evolution using high-resolution IR imagery, (c) Measure vertical profiles and transects of kinetic energy to estimate the advection and turbulence transport terms, (d) Deploy Unmanned Aerial Vehicles (UAVs) and tethered lifting systems (TLS) for whole flow field mapping, (e) Monitor mixed-layer depth in the valley and on the slopes, (f) Identify morning and evening transition mechanisms using IR imaging, distributed temperature measurement systems (DTS) and scanning LIDARS.

Implications: Accurate understanding of the coupling between surface flow and overlying atmosphere is needed for the models and model chains used for environmental prediction (Gopalakrishnan et al. 2000). High-resolution field data over diurnal cycles that focus on the effects of topographic inhomogeneities are non-existent, for which Perdigoão can make an impactful contribution.

4. Impacts of surface inhomogeneity

Hypotheses: Gradients of surface moisture, thermodynamic properties and roughness as well as slope discontinuities lead to 3D microcirculation, hydraulic adjustments and flow separation even when the slope and valley are nominally 2D. Such adjustments are significant when relevant local forcing is sufficiently strong. The local parameters determining microcirculation include in-situ land use/cover and surface properties (e.g., albedo, emissivity, hydraulic and thermal conductivity, roughness length, soil moisture), which broadly affect the surface energy budget. 3D flows so introduced lead to complex flow patterns (e.g. directional and horizontal shear; Fernando et al. 2001; Poggi et al. 2008).

Approach: (a) Collect high-resolution land-cover data just before the Perdigoão campaign to characterize elevation and vegetative canopy (e.g., topo-lidar, aerial photographs), (b) Site instruments at suitable (limited number of) locations with high spatial resolution for energy budget; some optimization will be necessary, (c) Conduct katabatic flow experiments in areas of different land cover and identify the differences of mean and turbulent flow properties, (d) Monitor flow adjustment regions at land-cover and slope-transition locations and map vertical variation of flow, (e) Identify spatial coherence of flow and scalar fields, (f) explain novel observations and conduct theoretical analyses.

Implications: Often, models assign a land use type based on the most covered land-use type within the computation grid, neglecting heterogeneities within. This approach needs a fundamental rethink. To this end, validation of existing land surface-atmosphere models with high-resolution data is imperative.

Performance of models at surface discontinuities (e.g., slope, land use) needs evaluation (Jiménez & Dudhia 2012; Rasouli & Hangan 2013; Castro et al. 2014), which most likely will call for model improvements.

5. Flow-turbine interactions and wake flows

Hypothesis: Coherent structures generated in a turbine wake can be effective momentum transfer mechanisms, depending on the background atmospheric stability. When a wind turbine is on a ridge, these wake structures can penetrate the valley and produce gusts and elevated turbulent kinetic energy regions that are non-stationary. Coherent structures may modify thermal circulation and land-surface thermodynamics, at least locally. Modification of pressure field by a turbine wake may affect flow separation on mountain slopes and valleys. (The presence of a single wind turbine on a mountain ridge at the Perdigão site (Section D.4) will help test this hypothesis).

Approach: (a) Investigate wake meander in horizontal and vertical directions using LIDARS, UAVs, and TLS, (b) Quantify TKE budgets in the wake and in the regions impacted by the wake, (c) Identify coherent-structure strikes on the topography via pressure fluctuations, and vertical momentum transfer from aloft by coherent structures, (d) Monitor interactions between coherent structures from the turbine and separated shear layers, and determine locations and mechanisms of interactions. (e) Conduct above studies for differing stability conditions.

Implications: There is increasing evidence that wind turbines wake regions can alter local flow (Rhodes & Lundquist 2013; Fitch et al. 2013; Rajewski et al. 2013), climatology (Zhou et al. 2012) and ecosystem health (Leung & Yang 2012; Premalatha et al. 2014; Dai et al. 2015). Yet wind energy is considered as one of the most environmentally clean energy resources. About 15-20% of the proposed wind power plants are not built because of the environmental concerns (IEA 2005), and wind wake impacts on the surface layer need to be accurately quantified if objective environmental impact assessments (EIA) are to be made. Thus, quantification of turbine influence on surrounding turbulence, energy budget, water vapor and CO₂ fluxes is imperative. Simultaneously collected turbulence data on crucial locations of wind turbine siting (upstream, top and lee of a hill) are non-existent, and must be collected at heights useful for surface-layer and wind turbine studies.

Modeling foci

Some of the important modeling issues related to Perdigão are: (a) Mechanisms by which small-scale, near-wall behavior affects large-scale motions over complex terrain (i.e., suitability of wall models and Monin-Obukhov theory; appropriate local averaging; inclusion of slope effects, stratification, spatial heterogeneity, roughness, vegetation, pressure gradients), (b) Optimal sensor placement strategies for microscale data assimilation over complex terrain (how many and what types? what siting strategies? sensor fusion and integration of data into models), (c) Coupling of models, especially two-way nesting (parameterizations for multi-scale interactions, nesting techniques, turbulence closures, land-surface model initialization), (d) Simulation of flow structures (coherent structures and their interactions with topography), (e) Inclusion of atmospheric stability in micro-scale models, including the appropriate level of complexity (micro-scale model simulations over large regions, proper representation of rapidly varying topographies in micro-scale models, studies on spectral representation of topography), (f) Representation of hill-induced shadowing heterogeneities (Dudhia terrain shadowing is used in WRF, but the absence of small-scale heterogeneities may pose errors; Can simple flux scaling laws be derived for land-use and shadow heterogeneities, say by using some modified roughness and thermal length scales?), (g) Downscaling of mesoscale models with a LES or RANS models (ensuring spin up of microscale model congruent with the output of the coarse model; see Muñoz-Esparza et al. 2014).

D.4 The Perdigão Field Study – Roadmap of European Scientists

As stated in D.1, the ERANET+ project for developing a European Wind Atlas involves a number of specialized field campaigns. In a workshop held in January 2011, the European Energy Research Alliance (EERA) announced that the primary land-based experiment would be in complex terrain, with emphasis on

extensive measurements up to the height of modern turbines (~ 150 m above the peaks). The prospective site should pose challenges for wind resource/load estimations, be representative of real wind farms and display major characteristics of complex sites, i.e., steep slopes and flow separation. A moderate level of complexity was sought to bridge the gap with previous studies. Earlier experiments have studied a single hill (e.g., Askervein) or an isolated escarpment (Bolund, Denmark; Bechmann et al. 2011), so after consideration of five different proposals from EU countries the workshop selected a double-ridge in central Portugal (Figures 4a,b), near the town of Perdigão.

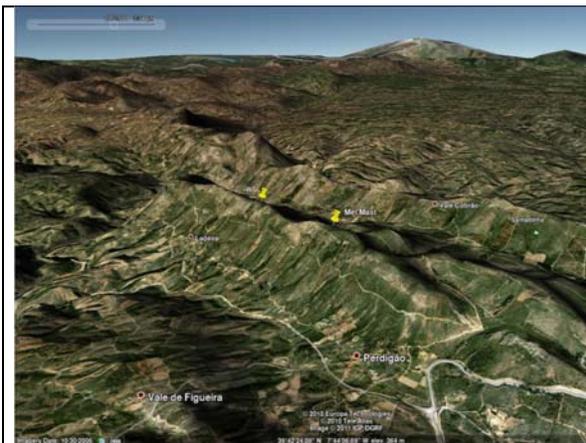


Figure 4a: The topography of Perdigão. Note the long two hill system with mild complexity. WT- wind turbine. Met mast is marked.



Figure 4b: The Perdigão site, looking SE from the turbine site, from the turbine location (note the newly laid power lines)

The advantages of this site are as follows:

- (i) As evident from Figure 2, it offers a parameter range not covered in previous studies, ($L/z_0 \sim 10^3$ with $h/L < 0.6$), except in the Cinder Cone Butte experiment where the focus was on flow visualization of a dividing stream line (Snyder et al. 1980).
- (ii) Although natural, it has only a mild complexity and is amenable for fundamental studies with easier interpretation of results. The topography is quasi-two dimensional, dominant winds are perpendicular to the ridges running SE - NW (Figure 5a), turbulence is nearly uniform in all horizontal directions (Figure 5b) and the site has only a few land cover types (Figure 4b).
- (iii) Two parallel ridges is one of the best formations that nature can offer to mimic a sequence of periodic hills; the results will be valuable for numerical modelers who seek periodic boundary conditions and/or two-dimensional simulations.
- (iv) Accessibility to all sides of the topography for instrument siting, with the lee flow of the first hill impinging on the second hill and vice versa. In between the hills is the valley flow; this can be a benchmark case for studies on the interaction of flow aloft with a valley flow and gap flows.
- (v) A meteorological mast has been operational at the site for several years, and a single wind turbine (Enercon 2MW/82m diameter) is already operational on one of the ridges (Figure 4a).

The preferred measurement height of EU scientists is 50-300m, which is the typical sweeping range of turbine rotors. Such heights are reachable using remote sensors and tall (200 m) towers. In addition, the deployment of Windscanner Triple Lidar systems will allow flow details to an unprecedented resolution. Windscanners are novel remote sensing technology developed by an EU consortium for probing the atmosphere, with unique applications to nominally inaccessible locations such as the coastal marine boundary layer, highly complex terrain and wind turbine wakes (Vasiljević et al. 2013; Vasiljević 2014). The system is based on cutting-edge wind Doppler Lidar technology, wherein each Lidar of the triumvirate measures the line-of-sight component of the wind. Controllable integrated steering of Lidar beams as well as their focus position by a master computer allow measurements within a hemispherical cone in a three-dimensional continuum of points, with a full top angle of ~ 180° and probe volume from ~ 60 m out to 6-9

km distance (size of the probe volume is dependent on the optics). Three line-of-site velocities so measured enable retrieval of the full wind velocity vector, without making any assumptions on the flow as required in single or dual- Lidar deployments. The instrument is able to produce detailed, full-scale, time-varying, three-dimensional maps of wind velocities, turbulence levels and Reynolds stresses, covering horizontal areas of tens of square kilometers (resolution ~ 150m), heights up to ~ 1km and a myriad of measurement surfaces including ‘mobile’ virtual towers. Measurement uncertainties are lower than those achieved by down-scaled wind tunnel testing or computer modeling. DTU will provide seven wind-scanner systems (21 LIDARS!) for the experiment – a remarkable asset.

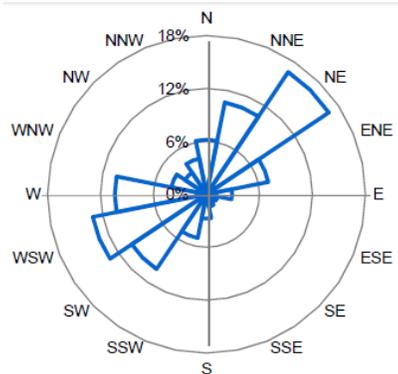


Figure 5a: Wind rose for Perdigão (Jan 2002–Dec 2004) based on a local 10 m met mast.

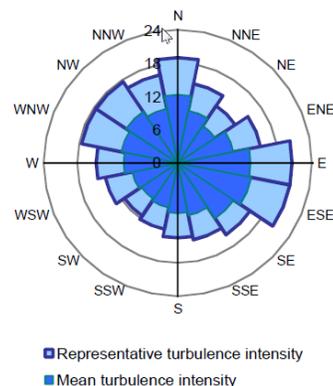


Figure 5b: Turbulent intensities for wind data shown in Figure 5a.

Table 2: Major US Science Community Activities Related to the Perdigão Experiment

Activity	Information/ Invitees/Attendees	Outcome
Initial meeting with Europeans, July 19, 2013 at Notre Dame	http://www3.nd.edu/~dynamics/20130719_WINDletter.pdf	Unanimous decision to participate in the Perdigão experiment
January 15, 2014	SPO/EDO Submitted	Declined, pending decisions from EU and NSF CentNet funding
Perdigão site visit by US and EU PIs, September 4-6, 2014	Steve Oncley (NCAR), Joseph Fernando (Notre Dame), Julie Lundquist (U. Colorado), Gordon Videen (Army Research Labs), ~ 10 participants from the EU team led by Jose Palma (U. Porto) http://www3.nd.edu/~dynamics/perdigao/Agenda_P_Visit.pdf	Site visit, discussed science issues and logistics, met with the Vila Velha de Ródão City Mayor
‘Microscale Modeling’ Meeting, Notre Dame, Sep 25-26.	Agenda and presentations: http://www3.nd.edu/~dynamics/perdigao/	Experimental design, science goals, confirmed instrument availability and EU support.

The experimental plan calls for some towers to be operated long term. Additional towers will operate during 2016-17, and a campaign with intensive operational periods (IOPs) is planned for 2017. In addition to traditional wind-energy relevant parameters such as wind profiles and turbulence, the experiment is to provide temperature gradients, turbulent fluxes of heat and humidity, all of which play a role in atmospheric stability that drastically affects flow at the height of large turbines. Extensive surface pressure measurements over the terrain are planned, allowing studies on how microscale and mesoscale flow models should be coupled. The sheer size of the experiment called for international scientific collaboration.

The EU project leaders invited the PIs and NCAR to explore the possibility of US institutions participating in the experiment. Pursuant to this invitation, a suite of activities followed (Table 2). The

consensus of the US scientific community was unanimous, in that the community could greatly benefit from participation in Perdigão. Consensus science issues to be pursued were listed in D.3

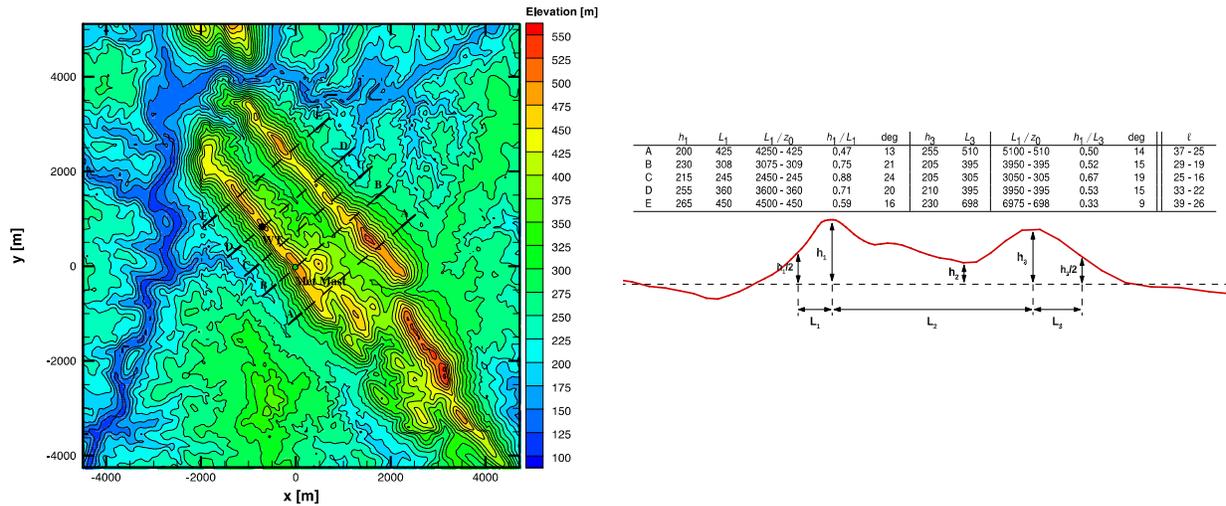


Figure 6: Elevation and slope description of five Perdigão transects identified for intensive instrument deployment based on pre-project modeling. Here ℓ is the ‘inner layer depth’ of Jackson & Hunt (1975).

D.5 Instrumentation Plan to Address Science Goals

The goal of the Perdigão experiment is to obtain data, with resolutions 500m to 1km in the horizontal and 10 to 100m in the vertical in selected regions and with coarser resolution elsewhere in the domain. VENTOS microscale modeling by the University of Porto shows that, in spite of nominally 2D topography, Perdigão flow can be highly 3D in some areas with regions of low and high winds, probably with some recirculation and high turbulence regions that should be carefully captured in the field campaign. Based on this modeling, during the initial planning of field deployments, five transects (A,B,C,D,E in Figure 6) across the valley were selected for intense instrumentation deployment, considering interesting physical processes and phenomena elicited by the simulations. This was the basis of deployment in the previous SPO/EDO. After a decision by the wind industry to install a high tension power line in the Southeast (Figure 4b), physical access to A and B was restricted and hence the plan needed revision for this SPO/EDO.

Considering science goals (Section D.3), confirmed instrumentation (Section I) and regulatory limitations, the deployment plan was revised from that of Figure 6, and the proposed layout based on the Notre Dame meeting outcome is shown in Figure 7. We perceive that only a limited number of issues in D.3 are tenable in the final program due to limitation of funds, and thus the proposed layout is designed to be sufficiently nimble for revision. Note that Figure 7 shows only the LAOF/EOL and European provided instruments, which adequately cover the area to achieve overall science goals. This is to be augmented by investigator-provided instrumentation after NSF funding decisions are made on individual projects. A view from the turbine location is shown in Figure 8, illustrating different but limited land use types.

At this juncture, the unique advantages of the seven Windscanner systems (Section I) should be reiterated. This technology offers wind and turbulence measurements with a spatial resolution of 40-100 m. Included in Figure 9 are the long range (WSL; 6-8 km) and short range (WSS; 1.5 km) systems to cover the entire region, including beam penetration to inaccessible areas (e.g., power-lines). Inflow and outflow to the valley from both predominant wind directions are well populated with towers and Windscanners. Figure 9 shows possible locations of Windscanners. Additional instrumentation such as SODARS/RASS will be added based on funded projects. Since LIDARS cannot measure fluxes of heat, moisture, etc., an array of surface flux systems will be used, augmented by the NCAR DIAL LIDAR (water vapor), along the wind turbine section. Further discussions on measurements are given in the Experimental Design Overview (EDO) document submitted to LAOF.

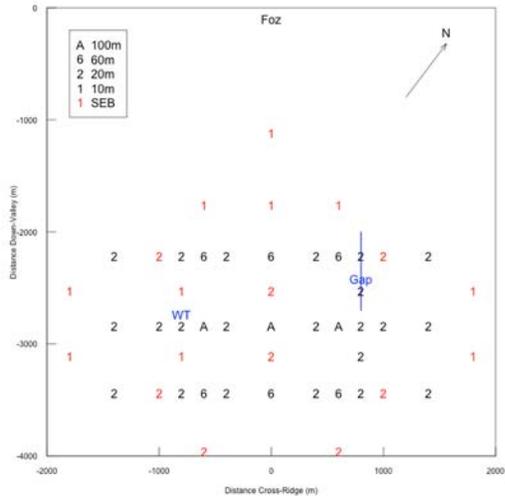


Figure 7: Layout of towers for Perdigão, coded by the tower height. The 18 towers with surface energy balance instrumentation are indicated in red (SEB). All 20m towers would have turbulence sensors at 2, 10, and 20m. The 60m towers would be instrumented at 2, 10, 20, 40, 60m, and 100m towers would also have instrumentation at 80 and 100m. The locations of the wind turbine (WT), ‘gap’ of interest in the NE ridge, and town of Foz do Cobre are shown. See Figure 9 for further details.



Figure 8: A north-west look from the turbine location. Gap – G, which is also evident in Figures 7 and 9. Diverse land cover/land use types can be seen, allowing investigations on their effects on the micrometeorological flows.

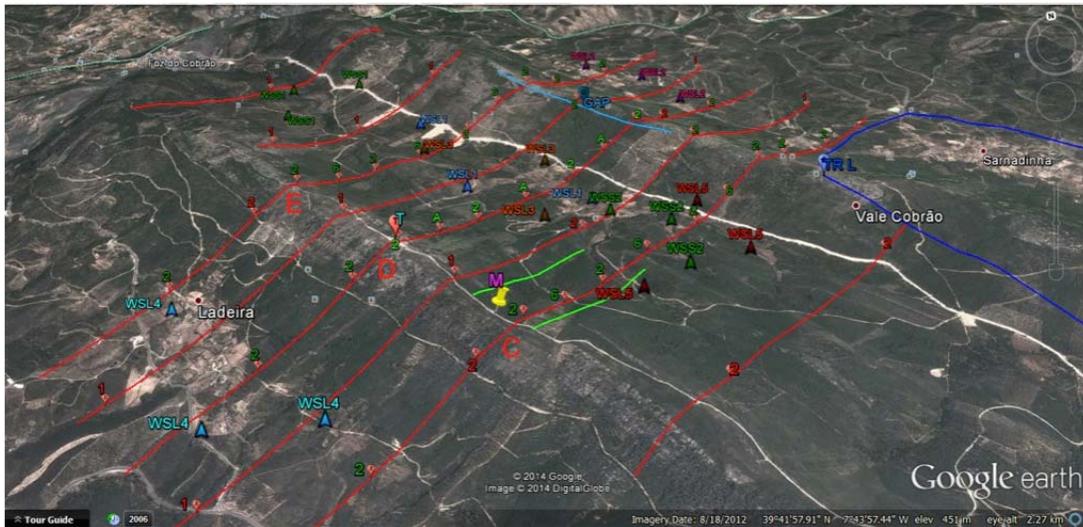


Figure 9: Instrumentation layout in eight along valley transects in Fig. 7a. The numerals have the same meaning. Short (WSS) and long (WSL) Wind scanners are numbered, with each system having three LIDARS. TLR – new transmission line. WSL4 and WSL2 – for approach/wake flows of the valley. Green lines - sites for slope experiments (different land use types, away from turbine wake).

D.6 Proposed Work

This proposal seeks nominal funding to conduct planning activities for US scientists to participate in the Perdigão field campaign and numerical studies. The field program anticipates the following schedule:

July 01, 2015: Initial monitoring by University of Porto begins, with limited instrumentation

March 2016: Investigator meeting (US and European) in the town of Vila Velha de Ródão, a city in the proximity of the field site

September 2016: Visit of PIs to Porto and the field site for further planning.

December 15, 2016: NEWA operations begin, with towers and Windscanner deployments. NCAR will add flux towers and profilers.

May 01-June 15, 2017: NSF/EU funded IOPs begin with full instrumentation. This period offers the best range of stability and climatological conditions as well as minimal conflicts with US academic schedules.

The proposed work under this SPO is as follows:

- a) **Conduct a workshop in the town of Vila Velha de Ródão**: We propose to hold a two-day workshop in March 2016 for further discussions on Perdigão science issues and strengthening collaboration. About ten US participants will be invited, and all NSF-funded investigators are expected to attend. Fine tuning of instrumentation sites and logistics for the operational period December 15, 2016 – June 30, 2017 will be high on the agenda. Discussions are expected to lead to further collaborative work between EU and US scientists. A half day visit to the experimental site is planned. Some funding will be allocated to other interested parties (e.g., ARL and NOAA) and invited speakers. The deliverables include: (i) a brief meeting report for the EOS newsletter and (iii) a report for public circulation (posted on the website).
- b) **Meetings between PIs and LAOF**: Several visits of the PI to Colorado are expected, to meet with co-PI, LAOF personnel and visiting EU investigators to NCAR.
- c) **A Second Perdigoao Visit**: The PIs and NCAR Coordinator Steve Oncley will make a second visit to Oporto for finalizing plans.

D.7. Intellectual Merits

Over the last few decades, a number of field experiments have been performed on atmospheric flow over nominally isolated hills. Perhaps the most referenced of all is the Askervein Hill experiment, the simplicity and idealized nature (i.e., a nearly two-dimensional isolated hill with horizontally homogeneous land cover and a predominant wind direction broadside to the hill) of which has contributed to its fame as the most influential data set to date. It has become the standard, against which most theories and modeling efforts base their skill. Much progress has been made since Askervein Hill, one of the most significant advancements lies in novel measurement technologies such as improved sonic anemometry, hot-wire combos, scanning Doppler LIDARS and Windscanners. Using combined intellectual and the state-of-the-art measurement resources of EU and US scientists, Perdigão promises to provide a more extensive, high-resolution, data set to complement, or perhaps replace, the Askervein Hill data as the benchmark. Perdigão will greatly enhance our knowledge on complex terrain flow physics and advance our ability to scientifically understand and characterize errors associated with application of linearized models in steep terrain and their impact on wind resource assessment.

D.8 Broad Impacts

The project has numerous direct societal benefits. It contributes to efficient harvesting of one of the cleanest, cost effective and renewable energy sources. To achieve energy independence, the US is seeking to provide 20% of its electricity by winds by the year 2030 (US DOE 2008; Shaw et al. 2009), for which a difficult challenge is the accurate mapping of wind resources (Lindenberg 2009). The associated Annual Energy Production (AEP) prediction errors are currently too large, and an increase of model resolution into the realm of microscale models is necessary. Errors of less than 1 ms^{-1} in estimating the annual wind resource for a typical wind farm can translate into many millions of dollars in annual revenues (Marquis et al. 2011). Perdigão is one of the first experiments with focus on improving microscale models for wind applications. The international collaboration will expose US PIs and students to global leading-edge technologies, for example, the new European Windscanner technology. If this SPO is successful, ensuing research proposals will request graduate student training, thus contributing to the development of a diverse,

globally competitive workforce in an area of national need. Several undergraduate students will also be hired as research assistants. Given the involvement of turbine manufacturers at Perdigão, the students will have direct contact with technology purveyors. The project will encapsulate diversity at all levels, from investigators to undergraduates. As in the past, in the context of this SPO the PI will seek support from the SLATT energy fellowship program for undergraduate research of the Notre Dame Energy Center. We have already identified a prospective student from an underrepresented group within STEM. As demonstrated by the Askervein study, data sets of the ilk of Perdigão will remain extremely useful for decades to come, so archiving and documentation of data and metadata will be an essential component of the project.

D.9 Results of Prior NSF Support

NSF award number - AGS 0934592; **Amount** - \$774,986; Period - 9/01/2009-31/08/2013

Title - CMG: Multiscale Modeling of Urban Atmospheres in a Changing Climate (PI: Alex Mahalov; Co PIs – Fernando, Wenbo Tang and Huei-Ping Huang)

Intellectual Merits: Canonical mesoscale models have been long known for ill specification of urban land use and related physics, which lead to difficulties of accurately capturing characteristic urban phenomena such as the urban heat island. This project developed and implemented, in the MM5v3.7 mesoscale modeling system, seven new urban categories and related dynamics. Improved boundary-layer physics were included via theoretical analysis of flow through building clusters (Zajic et al. 2015), flow transitions (Nadeau et al. 2011) and eddy diffusivity parameterizations (Monti et al. 2014). Anthropogenic heat flux from buildings and roadways as well as waterways were included, thus increasing model sophistication considerably (Park et al. 2014). Field experiments (Zajic et al. 2011, 2015; Dallman et al. 2013) as well as controlled laboratory (Fernando et al. 2010) studies were employed to the extent possible in delineating new physics. The new urbanized MM5 modeling system was evaluated against the canonical (un-urbanized) MM5, and impressive improvements were noted with regard to wind speed, temperature and momentum flux (Park et al. 2014). The improvement in the momentum flux, however, was marginal. In addition, a nested modeling system was developed to downscale IPCC (Assessment 4) climate model output to an urban microscale model (EnviMET) via Advanced Research Version of WRF. This modeling system was evaluated for current climate by a month-long urban field experiment in Chicago (Conry et al. 2015).

Broader Impacts: The project in part supported three students (i) Ann Dallman (PhD 2013, now at Sandia National Laboratory), Seoyeon Park (PhD 2013, Kepco Nuclear Graduate School, Korea), and Patrick Conry (PhD candidate; NDSEG Fellow). It led to collaboration with the City of Chicago, which funded climate downscaling work. The city uses project results to mitigate UHI and introduce cooling and energy efficiency strategies. The work was vividly highlighted by the Public Broadcasting Service at primetime - How to Build a Cooler City, PBS NEWSHOUR, <http://bit.ly/ChicagoCoping>, October 9, 2012.

Journal Publications: Fernando & Weil (2010), Fernando (2010), Fernando et al. (2010), Nadeau et al. (2010), Baklanov et al. (2011), Zajic et al. (2011, 2015), Lee & Fernando (2013), Dallman et al. (2013), Monti et al. (2014), Park et al. (2014), Conry et al. (2015), Leo et al. (2015).

Products: The data from the Chicago and Phoenix field studies are available for public use.

NSF award number - IIP-1332147; **Amount** - \$225,000; Period - 01/07/2013-30/06/2014

Title - STTR Phase I: Physics-based models of wind variability (PI: Mark Handschy; Co PI – Lundquist)

Intellectual Merit: This collaborative project between Enduring Energy, the University of Colorado, and Carnegie Mellon University, focused on transcending the empirical approaches typically used to characterize wind-power variability and developing instead robust statistical variability models, allowing results from one place or one time to be extended with known confidence to new locations and situations. The project supported one graduate student and one post-doc.

Journal Publications: St. Martin et al. (2015).

Broader Impacts: This STTR supported a female graduate student, Clara St. Martin.