

PAPER • OPEN ACCESS

Enhanced modelling of the stratified atmospheric boundary layer over steep terrain for wind resource assessment

To cite this article: A Flores-Maradiaga *et al* 2019 *J. Phys.: Conf. Ser.* **1222** 012005

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the **collection** - download the first chapter of every title for free.

Enhanced modelling of the stratified atmospheric boundary layer over steep terrain for wind resource assessment

A Flores-Maradiaga ^{a*}, R Benoit ^b, C Masson ^b

^a Department of Mechanical Engineering, Federico Santa María Technical University, Av. España 1680, casilla 110-V, Valparaíso, Chile

^b École de Technologie Supérieure, Université du Québec, Notre-Dame O 1100, H3C 1K3, Montréal, Québec, Canada

* E-mail: alex.floresm@usm.cl

Abstract. The Mesoscale Compressible Community (MC2) model [1], devoted for weather forecasting and used in the Wind Energy Simulation Toolkit (WEST) [2], performs well for simulations over flat, gentle and moderate terrain slopes but is subject to numerical instability and strong spurious flows in presence of steep topography. To remove its inherent computational mode and reduce the wind overestimation due to terrain-induced numerical noise, a new semi-implicit (N-SI) scheme [3] was implemented to discretize and linearize the non-hydrostatic Euler equations with respect the mean values of pressure and temperature instead of arbitrary reference state values, redefining as well the buoyancy to use it as the thermodynamic prognostic variable. Additionally, the climate-state classification of the statistical-dynamical downscaling (SDD) method [4] is upgraded by including the Brunt-Väisälä frequency that accounts for the atmospheric thermal stratification effect on wind flow over topography. The present study provides a real orographic flow validation of these numerical enhancements in MC2, assessing their individual and combined contribution for an improved initialization and calculation of the surface wind in presence of high-impact terrain. By statistically comparing the wind simulations with met-mast data, obtained within the Whitehorse area of the Canadian Rocky Mountains, it is confirmed that these numerical enhancements may reduce over 40 percent of the wind overestimation, thus, attaining more accurate results that ensure reliable wind resource assessments over complex terrain.

1. Introduction

Currently, the fast growing wind industry requires accurate and less uncertain wind resource assessment over diverse topographic configurations for wind farm planning and development. For this purpose, the Canadian Research Laboratory for Nordic Environment Aerodynamics of Wind Turbines (NEAT) has upgraded the mesoscale compressible community model (MC2) [1] as part of the latest improvements for the Wind Energy Simulation Toolkit (WEST), a widely used open-source software for wind resource assessment [2, 4]. Recently, the MC2 model has been upgraded with a built-in large eddy simulation (LES) methodology and advanced physical parameterization schemes [1, 5], which increase its capabilities to resolve nonlinear atmospheric flow phenomena over high impact orography.

However, it has been observed that MC2, similar to other mesoscale models that employ terrain-following coordinates, generates non-negligible spurious flows for wind simulations over complex terrain with moderate and steep slopes [4-7]. An important aspect of models that employ terrain-following σ -coordinates is that the pressure-gradient force may be miscalculated near steep slopes,



mostly due to the computational grid-cell deformation [8]. As demonstrated by Klemp [9], Zängl [10] and Blocken et al. [11], this terrain-induced spurious forcing is enhanced when an instable discretization scheme is applied, causing numerical noise and the overestimation of the surface wind speed at the mountain crests and lee-sides. This aspect is quite preoccupying for multiscale wind modelling, since wind farm engineering and financial decision-making depends heavily on the resource assessment results. Pinard et al. [12-13] and Gasset et al. [4] studies suggest that terrain-induced spurious forcing along with inappropriate initialization procedures significantly degrade the model's accuracy for real orographic flow realizations in highly complex sites.

Pinard's et al. [13] uncertainty diagnosis (i.e., modelled versus observation data) of MC2's performance for strongly stratified high-shear ABL flow simulations over mountainous topography in the western Canadian Rockies, confirm how the original semi-implicit (O-SI) discretization [1] in combination with the original wind-climate classification (OC) [2, 4] yield an overestimated mean velocity, directional shifting and strong spurious noise that degrade the consistency and accuracy of real case wind resource assessments.

The latter problem is corrected precisely with the new semi-implicit (N-SI) scheme [3], presented in section 2, which discretizes the model equations about the mean values of temperature (T_0) and pressure ($q_0 = \ln p_0$) and redefines the buoyancy -prognostic thermodynamic variable for MC2-, yielding a profound restructuration of the non-linear residuals to ensure numerical stability and control the computational mode. Additionally, the Brunt-Väisälä buoyancy frequency is added to the wind-climate new classification (NC) to account effectively for the thermal stratification along with wind speed, direction and shear. The SLEVE vertical coordinate [14] is also employed to ensure smoother terrain-conforming grid levels aloft so the irregular surface signal does not propagate unnecessarily into the domain's interior. Hence, the objective of the present study is the validation with real orographic flow of the combined enhancements for MC2, obtained from the N-SI time discretization scheme and the introduction of the Brunt-Väisälä buoyancy frequency in the SDD initialization scheme.

The combined enhancement obtained from the N-SI scheme and the new SDD wind-climate classification is expected to improve mostly the surface layer modelling and reduce the initialization errors for vertical momentum transport. It should enable an efficient and more accurate integration with high-order numerical algorithms, such as the semi-implicit semi-Lagrangian (SISL) solver [15-16]. The model is also supplemented with a second-order accurate Robert-Asselin-Williams (RAW) time-filter [17] to conserve better the system's total energy. The proposed enhancements are general enough to be applicable in any other multiscale model with similar numerical schemes.

2. Modified Model Equations

In general terms, the MC2 kernel solves the governing equations by separating the material derivatives applied on the prognostic variables ($d\Psi/dt$) and linear terms (\mathbf{L} , treated implicitly) from the non-linear terms (\mathbf{R} , treated explicitly), external forcing and source terms (\mathbf{F}), expressed in matrix form as follows:

$$\frac{d\Psi}{dt} + \mathbf{L} = \mathbf{R} + \mathbf{F}. \quad (1)$$

The semi-implicit semi-Lagrangian (SISL) discretization is applied on the first three terms of matrix system (1) to calculate the fluid particle's trajectory over three time-levels and, then, the external forcing and source terms are added in a fractional-step procedure [1]. Thus, the fundamental improvement introduced in system (1) is the restructuration of the linear \mathbf{L} and non-linear \mathbf{R} terms, in order to remove the computational mode and terrain-induced noise in the new formulation. As explained in [5], the momentum and heat turbulent fluxes are included in the \mathbf{F} terms after the governing equations are filtered, as required for large-eddy simulations. These turbulent fluxes need to be modeled using a particular SGS scheme in order to close the equation system.

The core system based on [1] includes the following momentum, energy and continuity equations:

$$\begin{aligned} \frac{d\mathbf{v}}{dt} + [\nabla - \gamma_* \mathbf{k}]P + \mathbf{k}(b - \gamma_A P) &= -f \mathbf{k} \times \mathbf{v} - \frac{b}{g}(\nabla - \beta_A \mathbf{k})P + \mathbf{f}, \\ \frac{d}{dt}(b - \gamma_* P) + N_*^2 w &= -b \left[\beta_A w + \frac{R}{c_v} \nabla \cdot \mathbf{v} \right] + \gamma_A Q, \\ \frac{d}{dt} \left(\frac{P}{c_*^2} \right) + \nabla \cdot \mathbf{v} - \frac{g}{c_*^2} w &= \frac{Q}{c_p T}, \end{aligned} \quad (2)$$

where $d/dt = \partial/\partial t + \mathbf{v} \cdot \nabla$ represents the material derivative, $\mathbf{v} = (u, v, w)$ the velocity, \mathbf{k} is the vertical direction unit vector, f the Coriolis parameter, $P = RT_* \ln(p')$ the generalized pressure, $p' = p - p_*$ the pressure perturbation, $b = g(T'/T_*)$ the buoyancy force, $T' = T - T_*$ the temperature perturbation, $\mathbf{f} = (f_u, f_v, f_w)$ the non-conservative forces and Q heat sources. The main variables are complemented with the speed of sound $c_*^2 = (c_p/c_v)(RT_*)$ and the natural oscillation frequency $N_*^2 = g\gamma_* = g(\beta_A + \gamma_A) = g^2/c_p T_*$, two fundamental parameters among with the constants $\beta_A = \partial \ln T_*/\partial z$ and $\gamma_A = g/c_p T_*$.

To enhance the model's numerical stability, an eigenmode analysis was applied on this equation system (2), discretized with the original semi-implicit scheme (O-SI), which revealed that the nonlinear terms relating the buoyancy with the pressure-gradient and flow divergence contribute significantly to the origin of numerical noise [3]. Thus, to overcome this inherent deficiency and ensure the hydrostatic balance, the buoyancy was redefined as $\hat{b} = g(T'/T) = g\alpha/(\alpha+1)$ with $\alpha = T'/T_*$, yielding a restructured system with a new semi-implicit (N-SI) discretization, as follows:

$$\begin{aligned} \frac{d\mathbf{v}}{dt} + \overline{(\alpha+1)(\nabla P + \mathbf{k}\hat{b})}^t - (\gamma_* + \gamma_A)\mathbf{k}P &= -f \mathbf{k} \times \mathbf{v} + \frac{\hat{b}}{g}\beta_A \mathbf{k}P + \mathbf{f}, \\ \frac{d}{dt} \left[(\alpha+1)\hat{b} - \gamma_* P \right] + \frac{\overline{N_*^2 w}}{\alpha+1} &= - \left(\frac{\alpha}{\alpha+1} \right) N_*^2 w + \gamma_A Q, \\ \frac{d}{dt} \left(\frac{P}{c_*^2} \right) + \nabla \cdot \mathbf{v} - \frac{\overline{g}}{(\alpha+1)c_*^2} w &= \left(\frac{\alpha}{\alpha+1} \right) \frac{g}{c_*^2} w + \frac{Q}{c_p T}, \end{aligned} \quad (3)$$

where the overbar $\overline{[\]}^t$ denote the implicit time averaging operator for terms solved over three time levels (3-TL). With this N-SI scheme, system (3) contains explicitly treated terms appropriately modified to recover the linearity in the hydrostatic relationship, which ensures the model's numerical stability in the presence of steep topography.

Based on the Boussinesq hypothesis, and using Einstein's notation, the turbulent stresses and heat fluxes can be expressed in terms of eddy- and heat-mixing coefficients ($\mu_t = \rho K_M$; $\text{Pr}_t = K_M/K_T$), the resolved strain rate $S_{ij} = 1/2[\partial \tilde{u}_i/\partial x_j + \partial \tilde{u}_j/\partial x_i]$, the sub-filter turbulent kinetic energy $\bar{\rho}k = 1/2\overline{\rho u'_i u'_i}$ and the potential temperature gradient, such that:

$$-\overline{\rho u'_i u'_j} = \tau_{ij} = 2\mu_t S_{ij} - 2/3(\mu_t S_{ii} - \bar{\rho}k) \quad \text{and} \quad -\overline{\rho u'_i \theta'} = \mu_t / \text{Pr}_t [\partial \tilde{\theta} / \partial x_i]. \quad (4)$$

Here the tilde represents the application of the implicit filter when the solution is projected onto the numerical grid. For this LES implementation in MC2, the classical Smagorinsky (SMAG) SGS scheme [18] is employed as a constant coefficient parametrization with stability functions based on the Richardson's number ($Ri = N^2/\bar{S}^2$) with $N^2 = (g/\bar{\theta})(\partial\bar{\theta}/\partial z)$ as the natural frequency of the air parcel's oscillation. The SMAG closure is formulated with the following relationships [5]:

$$\begin{aligned}
 K_M &= \lambda f_m \bar{S}, \quad K_T = \lambda f_h \bar{S}, \\
 \lambda &= \left[\frac{1}{C_s \Delta} + \frac{1}{\kappa (z + z_0)^2} \right]^{-1/2}, \\
 f_m &= \begin{cases} (1 - 16 Ri)^{1/2}, & 0 < Ri \\ \left(1 - \frac{Ri}{Ri_c}\right)^4, & 0 \leq Ri \leq Ri_c \end{cases} \\
 f_h &= \begin{cases} \frac{(1 - 40 Ri)^{1/2}}{Pr_t}, & 0 < Ri \\ \frac{(1 - 1.2 Ri)}{Pr_t} \left(1 - \frac{Ri}{Ri_c}\right)^4, & 0 \leq Ri \leq Ri_c \end{cases}
 \end{aligned} \tag{5}$$

where λ is the characteristic length scale, f_m and f_h are the stability functions for momentum and heat transport, respectively, $\bar{S} = 2(\mathcal{S}_{ij} - \delta_{ij}/2\mathcal{S}_{ii})$ is the corresponding strain rate tensor modulus for compressible flow simulations [19-20], C_s is the Smagorinsky coefficient, $\Delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$ is the filter length scale, $\kappa = 0.4$ is the von Kármán constant, z_0 is the aerodynamic roughness length, Ri_c is the critical Richardson number. A comprehensive explanation on the SGS scheme details and implementation for MC2 is provided by [5].

3. Validation of the enhanced modelling method

To demonstrate the advantageous features of the N-SI scheme to achieve enhanced numerical stability and the reduction of terrain induced noise, a canonical test with initially zero mean flow (i.e., atmosphere-at-rest simulation) is performed over flat terrain and a steep Gaussian hill with a maximum slope of 45° . An atmosphere-at-rest simulation requires an initialization with a hydrostatically balanced non-rotational atmosphere with zero horizontal velocity input, zero horizontal pressure gradient and a horizontally homogenous thermodynamic sounding. For these simulations, a free-slip condition and constant temperature are imposed on the surface. At the top of the domain a numerical sponge layer, based on Shuman's boundary condition [17], is set to restrict the spurious reflection of acoustic and gravity waves. These cases are initialized with an isothermal atmosphere, an ideal condition that simplifies the analysis of the temperature perturbation influence on the model's stability. The surface and isothermal reference temperatures are set to 250 K, which is a reasonable choice for mesoscale experiments [1].

The domain is $L_x = 10$ km long and $L_z = 5$ km high, with horizontal and vertical resolutions of $\Delta x = 100$ m and $\Delta z = 50$ m, respectively. For the time interval, preliminary testing revealed that $\Delta t = 10$ s is a good compromise for this grid resolution. Although the simulations are performed for 72 hours, with numerical instability there is no guarantee that the model would converge to the correct solution,

because the floating-point round-off or truncation errors can be magnified, instead of damped, causing the deviation from the exact solution to grow exponentially in an asymptotical fashion.

Figure 1 compares the mean flow fields obtained with the former and new model versions (Fig. 1a and 1b, respectively). Clearly, the N-SI scheme significantly reduces the terrain-induced noise and spurious flows by three orders of magnitude, which usually arise over the mountain slopes and propagate into the whole domain.

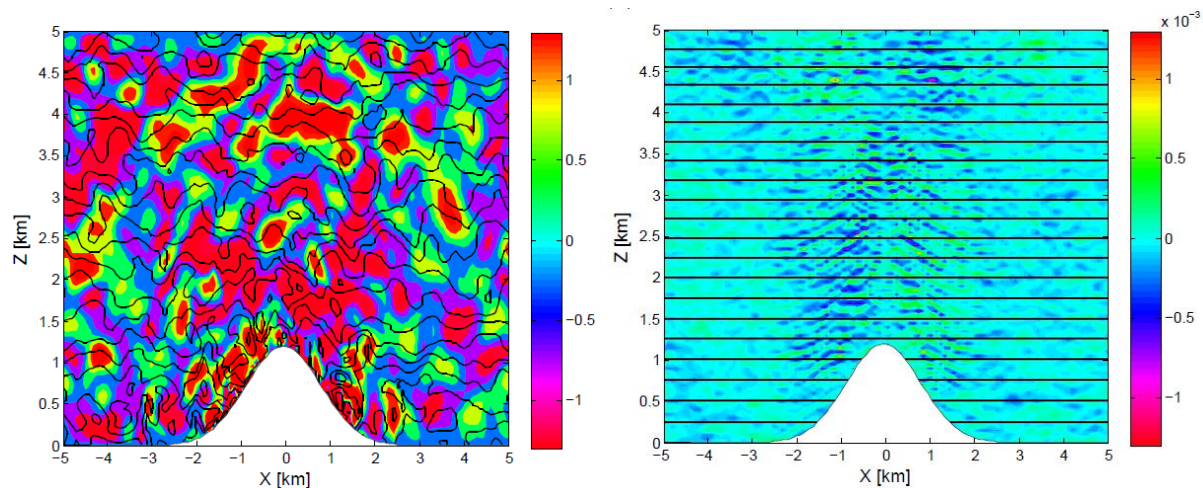


Fig. 1 – Comparison of mean wind field between the former (O-SI) and new (N-SI) model versions after 42 hours of an isothermal atmosphere-at-rest test. Solid lines denote potential temperature isentropes (interval of 2.5 K) and color shading represents the velocity (ms^{-1}). The right panel has a scale three orders of magnitude lower than the left panel since the numerical noise is significantly weaker.

Also, the maximum wind speed and noise kinetic energy spectra for both semi-implicit schemes are compared over flat and the 45° terrain slope in Figure 2, proving that the O-SI scheme is absolutely instable and highly noisy, contrary to the N-SI scheme that exhibits a controlled computational mode and low accumulation of kinetic energy for high-frequency small-scale structures. This achievement will allow the reduction of strong spurious flows behaving as fictitious turbulent wind with an energy cascade mechanism as depicted in Fig. 2b.

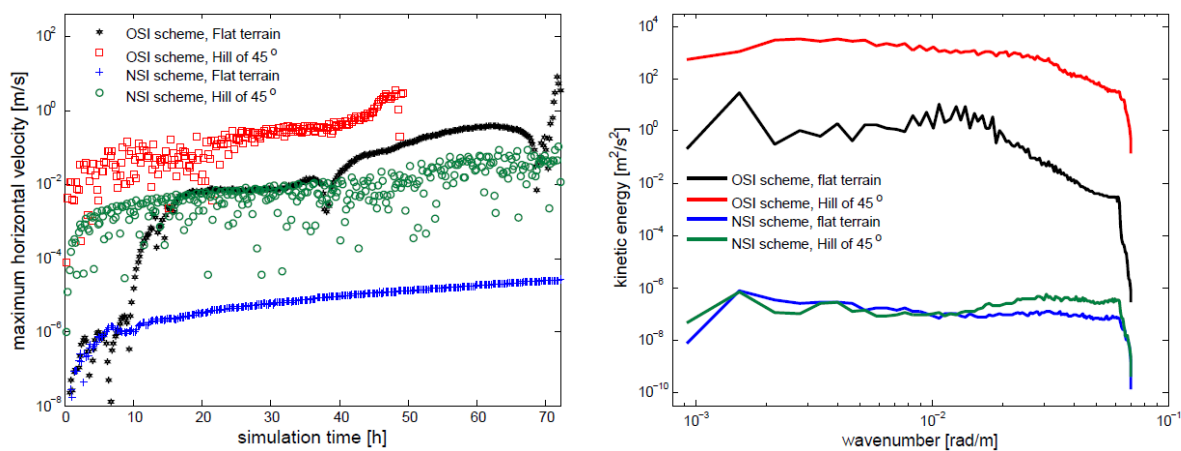


Fig. 2 – Comparison of (a) maximum wind speed and (b) noise energy spectra for flat and steep terrain the former (O-SI) and new (N-SI) model versions after 42 hours of an atmosphere-at-rest test.

The O-SI scheme generates an asymptotically growing computational mode over both flat and complex terrain, which inevitably yields an extremely noisy and unstable model. Complex terrain amplifies the high-frequency noise at least one order of magnitude and leads to an early blow-up of the unstable model. Steep hill slopes magnify spurious flows, which could erroneously be considered as mountain top speed-up or lee-side wind storms, leading to wind speed overestimation in real mesoscale applications. We distinguish an extended dissipation range ($k > 10^{-2} \text{ m}^{-1}$) in the O-SI noise spectrum, which resembles the physical turbulence dissipation range. Thus, the O-SI spurious circulations behave as numerically generated turbulence that can contaminate atmospheric boundary layer simulations. The O-SI scheme alone is notoriously unable to perform accurately and cannot yield reliable results due to its inherent instability and strong numerical noise generation.

To demonstrate that the combined N-SI and NC schemes implemented in MC2 effectively reduce the wind-speed overestimation, we simulate the wind over the cold-climate mountainous Whitehorse area (Fig. 3a) in the Yukon Territory of Western Canada. As mentioned in [12], sites of interest for wind energy development in this area have steep slopes that exceed 15° . This area is bordered and influenced by the Wrangell St. Elias Mountains, Western Costal Mountains, Mackenzie Mountains and Canadian Rocky Mountains. The landscape is covered with prominent ice-capped peaks, deep valleys, rivers and lakes, where the majority of terrain features range between 1000 and 3000 m ASL, among which Mount Logan stands out with a maximum height of 5959 m ASL. The local climate conditions and seasonal wind flow variations are highly influenced by the mountainous forcings and strong thermal stratification.

In order to relate to previous studies by Pinard et al. [13], we employ the same values for grid size (square lateral length of 100 km and height of 10 km), grid's horizontal resolution ($\Delta x = \Delta y = 1 \text{ km}$, with $100 \times 100 \times 100$ grid-points), domain layering (vertically stretched with 12 layers in the first 1500 m above ground level), time interval ($\Delta t = 60 \text{ s}$) and the total simulation time (16 hrs, which ensures quasi-steady convergence after 12 hrs and integration period). A column-type URANS scheme is used for turbulence parameterization. The simulation is performed with the log-law surface model, lateral boundary conditions obtained from a synoptic scale model and a Shuman [21] wave absorbing sponge at the top 10 layers to avoid gravity wave reflection that could bias the results.

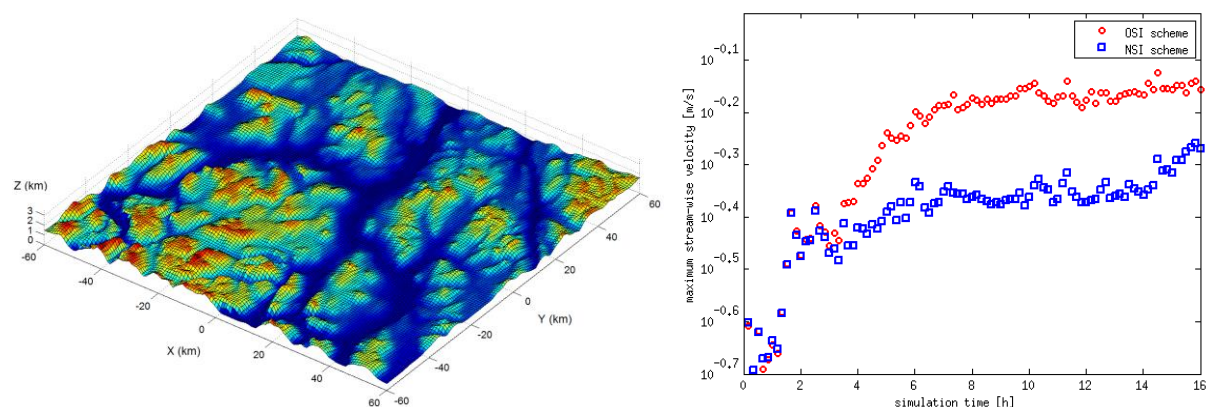


Fig. 3 – (a) Illustration of the Whitehorse valley at 1 km resolution and (b) the evolution of the numerical noise for streamwise surface wind speeds (ms^{-1}) after 16 hours of an atmosphere-at-rest simulation.

Before running the orographic flow case, a atmosphere-at-rest test is performed over this complex terrain to assess the propagating gravity oscillations under stringent conditions, with a strongly stable atmosphere initially at rest with underlying multiscale ridges. In Fig. 3b we observe that the wind speed starts with a similar magnitude for both SI schemes and grows asymptotically as the integration progresses. However, the maximum horizontal velocities obtained with the N-SI scheme display an approximate reduction of 30% with respect to the O-SI results. This noise reduction, achieved by the N-

SI scheme alone without any other stabilizing mechanism (i.e. decentering or filtering), certainly enhances MC2's accuracy and numerical stability by weakening its spurious computational mode.

Then, proceeding with the real orographic flow over the Whitehorse area, a full set of simulations were initialized with the SDD algorithm that automatically defines the number of situations to model, depending on the chosen wind climate-state classification (OC yields 224 cases and NC yields 896 cases). Table 1 summarizes the statistical assessment of the former or baseline (OC+O-SI) and novel (NC+N-SI) scheme combinations upon the comparison of modelled versus observed data, measured at 30 m above ground level by 16 wind-stations distributed in the Whitehorse valley. The NC+O-SI only yields a 0.045 ms^{-1} reduction of the MAE respect to the baseline combination, which represents an improvement of 4.6% obtained only by using a better SDD initialization algorithm. With the OC+N-SI combination, we achieve a reduction of the wind MAE by 0.41 ms^{-1} , which translates into a 42.4% improvement with respect to the baseline schemes since the spurious acceleration is attenuated. Finally, the two schemes together as NC+N-SI yield the best flow field readjustment, attaining a 0.44 ms^{-1} reduction of the wind MAE, i.e. 45.4 % improvement, that ensures a higher accuracy for wind resource assessment. The average and standard deviation of wind speed are reduced significantly, achieving much higher correlations between modelled and observed values and almost half the mean absolute error (MAE) with the NC+NSI combination.

Table 1 Statistics of the numerical simulations of stratified wind in the Whitehorse valley.

Schemes	Average (ms^{-1})	Minimum (ms^{-1})	Maximum (ms^{-1})	σ_U (ms^{-1})	Correlation model-obs.	Mean Abs. Error (ms^{-1})	MAE reduction
OC+OSI	4.3392	2.7493	6.7301	1.1107	0.7485	0.9687	-
NC+OSI	4.2709	2.8268	6.4874	1.0671	0.7669	0.9238	4.64 %
OC+NSI	3.7669	2.1601	7.0317	0.6811	0.9175	0.5584	42.35 %
NC+NSI	3.8106	2.0973	7.2712	0.6589	0.9299	0.5291	45.38 %

Replicating correctly the surface flow pattern over prominent mountain and valley features is a key challenge to achieve an effective improvement in multiscale wind resource assessment. Fortunately, the NC+N-SI scheme combination imbedded in the SDD method yields a correction of the surface flow field misrepresented with OC+O-SI. Figure 4 depicts the mean wind field realizations over the Whitehorse valley, that is expected to flow east-northward based on the observed and reanalysis data. Clearly, the OC+O-SI baseline combination (Fig. 4a) fails to obtain appropriate wind speeds and directions. In fact, it reveals that this baseline permutation significantly overestimates the wind magnitudes when the air masses interact with steep terrain slopes. Although the OC+O-SI combination is able to replicate the deep valley flow channeling, the adverse influence of the miscalculated wind aloft yields a wrong vector orientation with recirculation and flow inversion in the valleys.

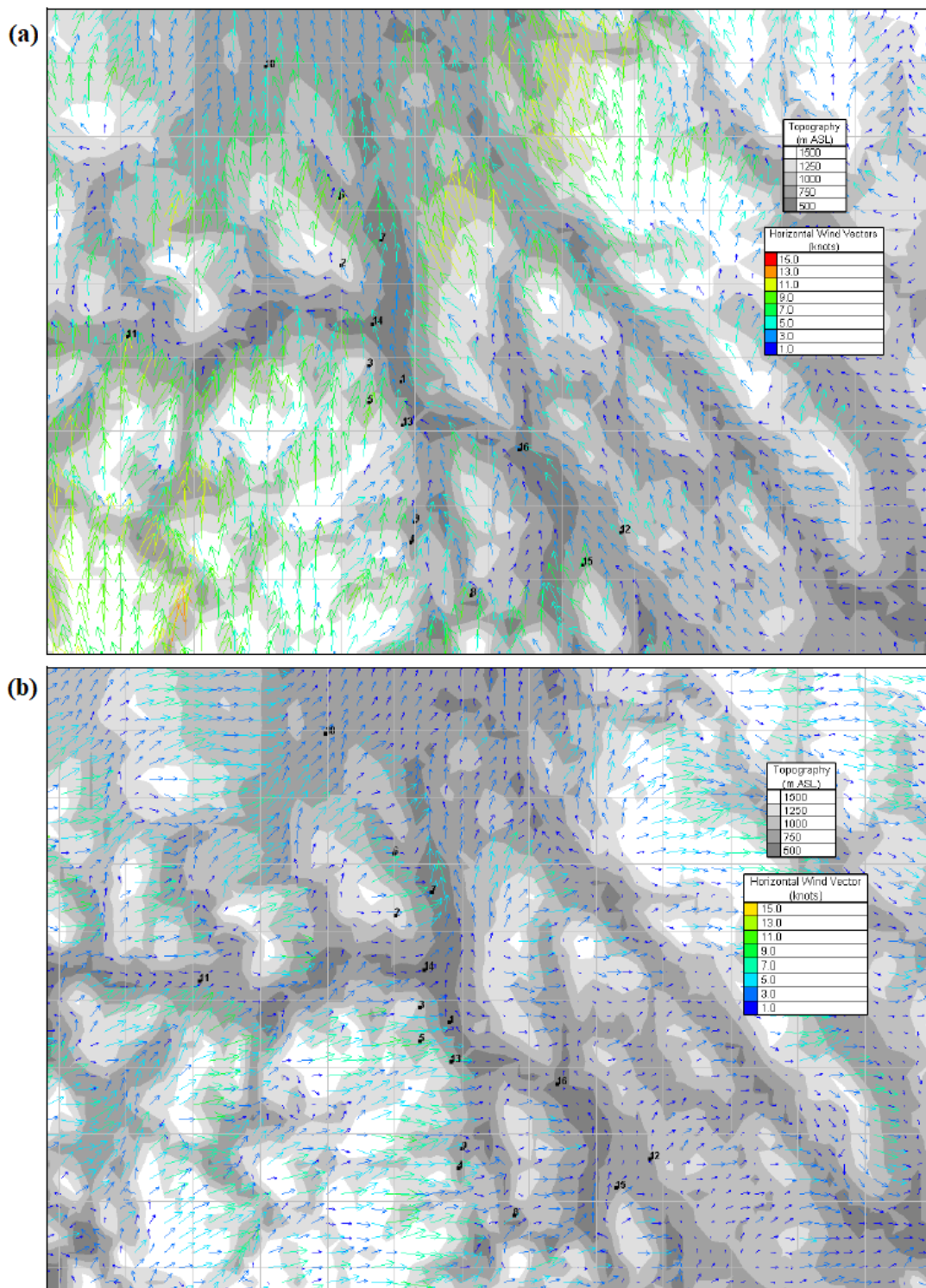


Fig. 4 – Mean wind flow patterns at 30 m AGL in the Whitehorse valley, obtained with the (a) OC+OSI and (b) NC+NSI combinations implemented in MC2.

Indeed, the cold airflow in this site should be oriented primarily east-wise, with nearly half of the magnitude, as it is evident in the NC+N-SI realization (Fig. 4b). The former scheme combination also achieves the expected mountain-valley systems, with low-level jets over the hilltops and cross

channeling within the valleys. Hence, the proposed enhancements for the MC2 model and SDD algorithm will, most likely, correct the long-standing difficulties faced by WEST and similar wind resource assessment toolkits for ABL simulations over steep complex terrain.

4. Conclusions

Without any damping or filtering mechanisms, for a resting stratified atmosphere over complex terrain, the N-SI scheme yields a noise reduction of nearly 30% with respect to the O-SI results. The analysis of the ABL simulations with the proposed new semi-implicit discretization and the new wind-climate classification for SDD initialization indicates that, in presence of steep mountain slopes, MC2 effectively attains an error reduction of 40% or more as compared to the former schemes. The overall improvement, with 45.38% MAE reduction, 93% correlation and half the standard deviation, reflects that the combined NC+NSI contribution is the best for orographic flow modelling over steep complex terrain. Although modest, these improvements contribute to the uncertainty reduction for wind resource assessment over complex topography.

Acknowledgements

The authors want to thank the Canadian National Science and Engineering Research Council (NSERC) for funding this research through project WESNet 1.1-a, as well as the Chilean National Commission for Scientific and Technological Research (CONICYT) for funding this research through project FONDEF ID16I10105. We also wish to thank the Environment and Natural Resources Department of Canada and, particularly, Dr. Claude Girard and Dr. Nicolas Gasset for providing the MC2 code, technical support and counselling during this study.

References

- [1] Girard C, Benoit R and Desgagné M 2005 *Finescale topography and the MC2 dynamics kernel* Monthly Weather Review **133** 1463–1477
- [2] Yu W, Benoit R, Girard C, Glazer A, Lemarquis D and Pinard 2006 *Wind Energy Simulation Toolkit (WEST): A Wind Mapping System for Use by the Wind Energy Industry* Wind Engineering **30** 15-33
- [3] Flores-Maradiaga A, Benoit R and Masson C 2016 *Enhanced Method for Multiscale Wind Simulations over Complex Terrain for Wind Resource Assessment* Journal of Physics: Conf. Series **753** 082030
- [4] Gasset N, Laundry M and Gagnon Y 2012 *A Comparison of Wind Flow Models for Wind Resource Assessment in Wind Energy Applications* Energies **5** 4288–4322
- [5] Gasset N, Benoit R and Masson C 2014 *Implementing Large-eddy Simulation Capability in a Compressible Mesoscale Model* Monthly Weather Review **142** 2733-2750
- [6] Fleming P, Churchfield M, Scholbrock A, Michalakes J, Johnson K and Moriarty P 2013 *The SOWFA super-controller: a high-fidelity tool for evaluating wind plant control approaches* National Renewable Energy Laboratory NREL/CP **5000** 57175
- [7] Lundquist K, Chow F K and Lundquist J 2010 *An Immersed Boundary Method for the Weather Research and Forecast Model* Monthly Weather Review **138** 796 – 817
- [8] Shchepetkin A and McWilliams J 2003 *A method for computing horizontal pressure gradient force in an ocean model with a non-aligned vertical coordinate* Journal of Geophysical Research **108** 3090
- [9] Klemp J 2011 *A Terrain-following Coordinate with Smoothed Coordinate Surfaces* Monthly Weather Review **139** 2163–2169
- [10] Zängl G 2012 *Extending the Numerical Stability Limit of Terrain-Following Coordinate Models over Steep Slopes* Monthly Weather Review **140** 3722–3733

- [11] Blocken B, Hout A, Dekker J and Weiler O 2015 *CFD Simulations of Wind Flow over Natural Complex Terrain: Case Study with Validation by Field Measurements for Ria de Ferrol, Galicia, Spain* Journal of Wind Engineering and Industrial Aerodynamics **147** 43-57
- [12] Pinard J P, Benoit R and Yu W 2005 *A WEST Wind Climate Simulation of the Mountainous Yukon* Atmosphere-Ocean **43** 259-282
- [13] Pinard J P, Benoit R and Wilson J D 2009 *Mesoscale Wind Climate Modelling in Steep Mountains* Atmosphere-Ocean **47** 63-78
- [14] Schär C, Leuenberger D, Fuhrer O and Girard C 2002 *A New Terrain-following Vertical Coordinate Formulation for Atmospheric Prediction Models* Monthly Weather Review **130** 2459–2480
- [15] Tanguay M, Robert A and Laprise R 1990 *A Semi-Implicit Semi-Lagrangian Fully Compressible Regional Forecast Model* Monthly Weather Review **118** 1970–1980.
- [16] Thomas S, Girard C, Benoit R and Pellerin P 1998 *A New Adiabatic Kernel for the MC2 Model* Atmosphere–Ocean **36** 241–270
- [17] Williams P D 2011 *The RAW Filter: an Improvement to the Robert-Asselin Filter in Semi-Implicit Integrations* Monthly Weather Review **139** 1996–2007
- [18] Smagorinsky J 1963 *General Circulation Experiments with the Primitive Equations. Part 1: The Basic Experiment* Monthly Weather Review **91** 99–152
- [19] Cuxart J, P Bougeault and J L Redelsperger 2000 *A Turbulence Scheme Allowing For Mesoscale and Large-Eddy Simulations* Quart. J. Roy. Meteor. Soc. **126** 1-30
- [20] Drobinski P, Carlotti P, Redelsperger J L, Banta M, Masson V and Newsom R 2007 *Numerical and Experimental Investigation of the Neutral Atmospheric Surface Layer* J. of Atmospheric Sciences **64** 137–156
- [21] Shuman F 1957 *Numerical Methods in Weather Prediction: (II) Smoothing and Filtering* Monthly Weather Review **85** 357–261