New roughness treatment in ISBA scheme

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Introduction

- **surface roughness** z_0 is a key quantity for turbulent transport of momentum, heat and moisture in surface layer, as witnessed by logarithmic wind profile:

$$u(z) = \frac{u_*}{\kappa} \ln\left(1 + \frac{z}{z_0}\right)$$

u_* – friction velocity
κ – von Kármán constant
z – height over zero-plane

- in 1990s it was found that **form drag** due to unresolved orography can be represented by increased dynamical roughness z_{0D}

$$\Downarrow$$

concept of **effective roughness**
(positive impact on momentum budget in NWP models)

- to the leading order, there should be **no effect** of unresolved orography on turbulent transport of **heat and moisture**

- activation of this idea in ALARO-1 revealed several problems with roughness treatment in ISBA scheme

Monin-Obukhov equations

- surface roughness comes from Monin-Obukhov equations:

$$\frac{\mathrm{d}u}{\mathrm{d}z} = \frac{u_*}{\kappa(z + z_{0\mathrm{D}})} \varphi_\mathrm{M}\left(\frac{z + z_{0\mathrm{D}}}{L}\right)$$

$$\frac{\mathrm{d}s}{\mathrm{d}z} = \frac{s_*}{\kappa(z + z_{0\mathrm{H}})} \varphi_\mathrm{H}\left(\frac{z + z_{0\mathrm{H}}}{L}\right)$$

$$L = \frac{s(0)u_*^2}{\kappa g s_*}$$

u	– wind speed
s	– dry static energy
u_*, s_*	– friction values
φ_M, φ_H	– universal functions
L	– Monin-Obukhov length

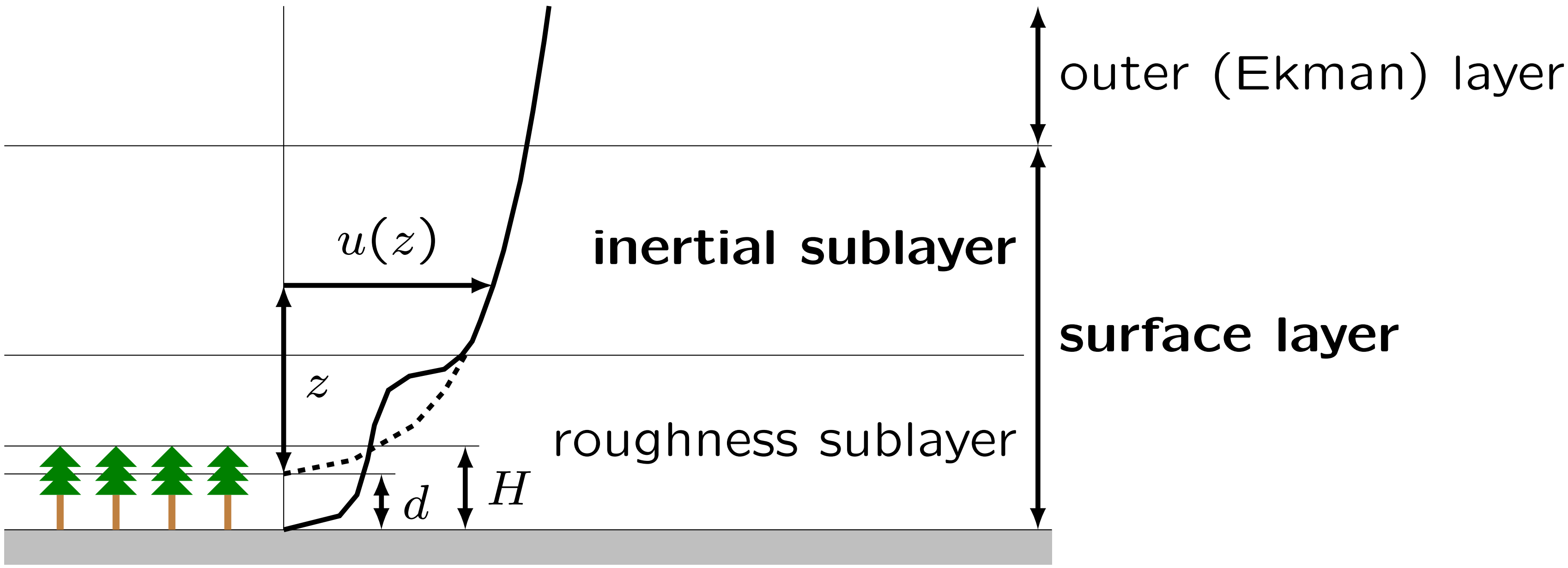
- friction values u_*, s_* are defined via turbulent fluxes of momentum and heat in surface layer ($u_* \geq 0$ while s_* can have any sign):

$$\rho u_*^2 = \rho\sqrt{\overline{u'w'}^2 + \overline{v'w'}^2} \qquad \rho s_* u_* = -\rho\overline{s'w'}$$

- there are two different roughness values – **dynamical roughness** $z_{0\mathrm{D}}$ and **thermal roughness** $z_{0\mathrm{H}}$
- thermal roughness $z_{0\mathrm{H}}$ is applied to heat and moisture
- in ARPEGE/ALADIN, **constant ratio** $z_{0\mathrm{D}}/z_{0\mathrm{H}} = 10$ is assumed

Validity region

- Monin-Obukhov similarity theory holds in the surface layer, except from its bottom part where the mean flow is perturbed by turbulent wakes of individual roughness elements



- surface layer typically occupies ~10% of atmospheric boundary layer
- depth of roughness sublayer is 2–5 times canopy height H
- extrapolation of logarithmic wind profile into roughness sublayer gives zero wind at displacement height d, usually between $\frac{2}{3}H$ and $\frac{3}{4}H$

Drag and heat coefficients

- **bulk parameterization** expresses turbulent fluxes in surface layer via differences of u and s between the lowest model level $z = Z$ and surface $z = 0$:

$$\rho\sqrt{\overline{u'w'}^2 + \overline{v'w'}^2} = \rho C_\text{D} u^2(Z)$$
$$-\rho\overline{s'w'} = \rho C_\text{H} u(Z)[s(Z) - s(0)]$$

- proportionality factors – drag and heat coefficients – depend on both stability and roughness:

$$C_\text{D} = F_\text{M}(Ri) \cdot C_\text{DN} \qquad C_\text{DN} = \frac{\kappa^2}{\ln^2\left(1 + \frac{Z}{z_{0\text{D}}}\right)}$$

$$C_\text{H} = F_\text{H}(Ri) \cdot C_\text{HN} \qquad C_\text{HN} = \frac{\kappa^2}{\ln\left(1 + \frac{Z}{z_{0\text{H}}}\right) \ln\left(1 + \frac{Z}{z_{0\text{D}}}\right)}$$

- stability functions F_M and F_H are related to Monin-Obukhov universal functions

- in TOUCANS they depend only on **bulk Richardson number** Ri

Role of dynamical roughness

- primary role of dynamical roughness $z_{0\mathsf{D}}$ is to parameterize turbulent **shear stress:**

$$\tau_{\mathsf{shear}} = \rho F_{\mathsf{M}}(Ri)\, C_{\mathsf{DN}}\left(\frac{Z}{z_{0\mathsf{D}}}\right) u^2(Z)$$

- secondary role is to represent also turbulent **form drag** due to subgrid-scale orography, achieved by use of higher **effective roughness** $z_{0\mathsf{D}}^{\mathsf{eff}}$:

$$\tau_{\mathsf{shear}} + \tau_{\mathsf{form}} = \rho F_{\mathsf{M}}(Ri)\, C_{\mathsf{DN}}\left(\frac{Z}{z_{0\mathsf{D}}^{\mathsf{eff}}}\right) u^2(Z)$$

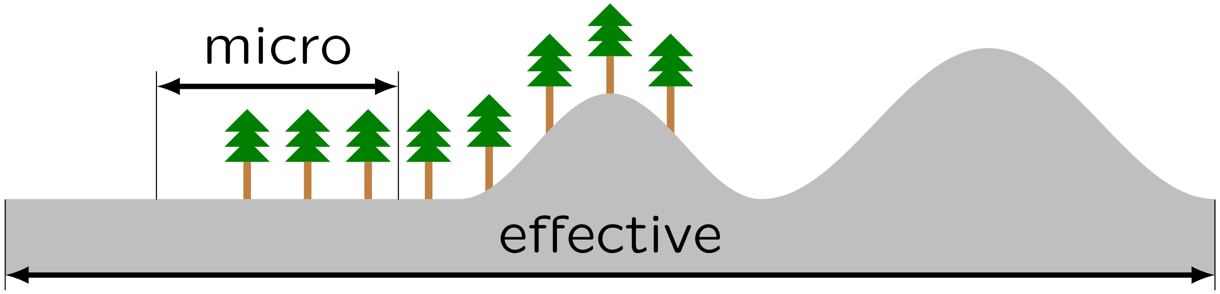
- effective dynamical roughness improves surface momentum flux at the expense of too slow wind on few bottom model levels

- more direct way of dealing with subgrid-scale orography is to introduce separate term in momentum equation

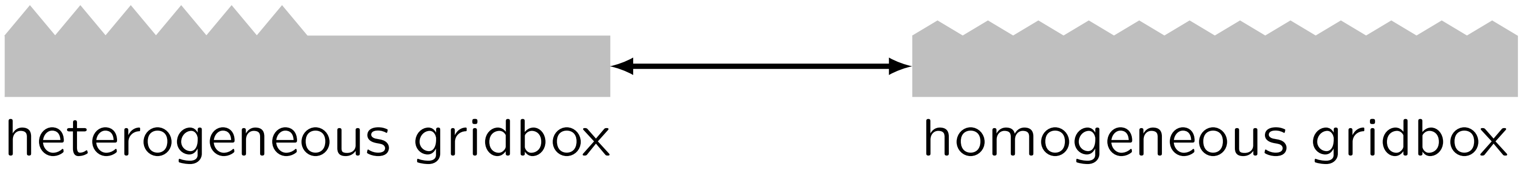
- this is done in parameterization of orographic drag, comprising gravity wave drag, form drag and lift (subroutine ACDRAG)

Terminology

- to prevent confusion, two types of dynamical roughness must be distinguished, differing by upper scale of assumed roughness elements:
  - **micrometeorological roughness** – given by material properties, vegetation, and urban structures (horizontal scales up to $\sim$100 m)
  - **effective roughness** – includes also contribution of subgrid-scale orography (horizontal scales up to Δx)



- **CAUTION:** in the literature, effective roughness sometimes denotes gridbox averaged micrometeorological value



Effective dynamical roughness

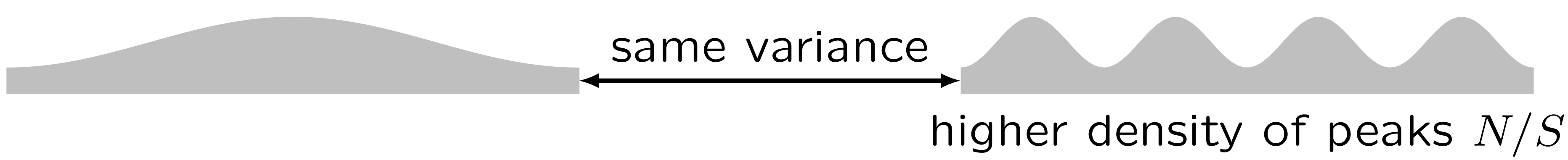
- effective roughness z_{0D}^{eff} represents combined effect of micrometeorological roughness and subgrid-scale orography:

$$z_{0D}^{\text{eff}} = \sqrt{(z_{0D})^2 + (z_{0D}^{\text{orog}})^2}$$

- roughness due to subgrid-scale orography z_{0D}^{orog} is defined as:

$$z_{0D}^{\text{orog}} = \underbrace{(\overline{h^2} - \overline{h}^2)}_{\text{variance}} \sqrt{\frac{N}{S}}$$

h – height of subgrid-scale orography
N – number of peaks in gridbox
S – gridbox area



- underlying topographic dataset must have **sufficient resolution** to provide reliable orographic roughness

- configuration e923 calculates orographic roughness from GTOPO30, scales it by factor FACZ0 and applies smoother NLISSZ times

Treatment of thermal roughness

- until recently, ALARO used an old treatment **increasing** also thermal roughness due to subgrid-scale orography (option LZ0HSREL=F)

- constant ratio of dynamical to thermal roughness was kept also for their effective values:

$$z_{0\mathrm{H}}^{\mathrm{eff}} = z_{0\mathrm{D}}^{\mathrm{eff}}/10 = \sqrt{(z_{0\mathrm{H}})^2 + (z_{0\mathrm{D}}^{\mathrm{orog}}/10)^2}$$

- for small slopes, however, turbulent transport of heat/moisture should not be affected by subgrid-scale orography (Hewer and Wood 1998)

- preservation of heat coefficient C_H implies **smaller** effective thermal roughness $z_{0\mathrm{H}}^{\mathrm{eff}}$, such that:

$$\ln\left(1 + \frac{Z}{z_{0\mathrm{H}}^{\mathrm{eff}}}\right) \ln\left(1 + \frac{Z}{z_{0\mathrm{D}}^{\mathrm{eff}}}\right) = \ln\left(1 + \frac{Z}{z_{0\mathrm{H}}}\right) \ln\left(1 + \frac{Z}{z_{0\mathrm{D}}}\right)$$

- this new treatment was operational in ARPEGE since November 2010, improving screen level scores over orography (option LZ0HSREL=T)

Roughness in climate files

- in configuration e923, content of roughness fields is controlled by namelist key LZ0THER:

FA field \ LZ0THER	T	F
SURFZ0.FOIS.G	gz_{0D}^{eff}	gz_{0D}^{eff}
SURFGZ0.THERM	$gz_{0D}^{eff}/10$	$gz_{0D}/10$

- roughness fields in FA file are multiplied by gravity acceleration g
- dynamical roughness SURFZ0.FOIS.G always contains effective value
- thermal roughness SURFGZ0.THERM contains either scaled effective dynamical value or micrometeorological value
- valid combinations of LZ0THER with integration option LZ0HSREL:

setting \ key	LZ0THER	LZ0HSREL
old	T	F
new	F	T

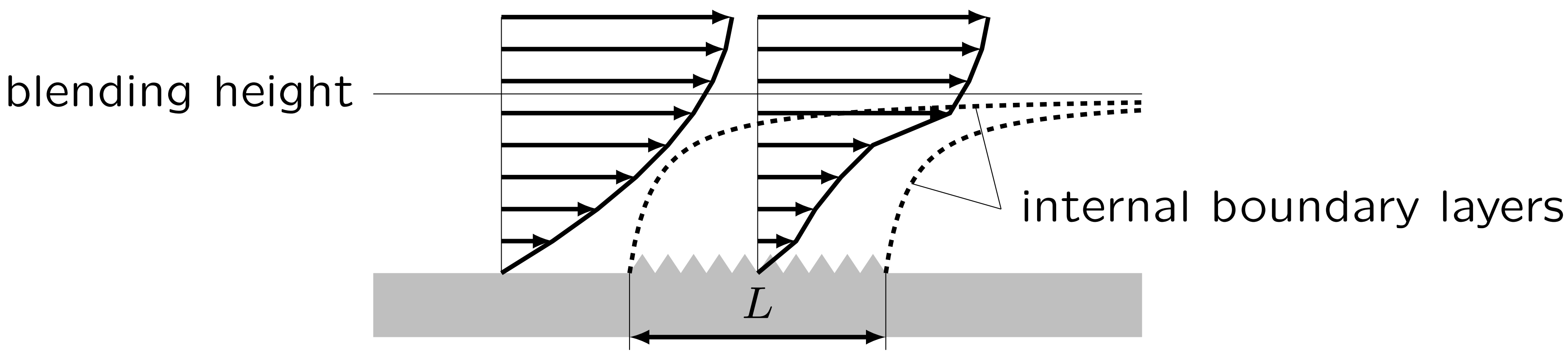
Roughness averaging

- gridbox roughness in ISBA scheme is averaged between its snow free and snow covered parts (weighted by snow fraction)
- ideally, averaged quantity should be corresponding turbulent flux
- when the lowest model level is in properly chosen height Z, flux averaging reduces to averaging of drag and heat coefficients
- in neutral conditions, averaged quantity should be $1/\ln^2\left(1+\frac{Z}{z_{0\mathrm{D}}}\right)$
  - in formal limit $Z \ll z_{0\mathrm{D}}$ it results in averaging of $(z_{0\mathrm{D}})^2$, consistent with quadratic inclusion of orographic roughness
  - in the opposite limit $Z \gg z_{0\mathrm{D}}$ it results in averaging of $1/\ln^2\left(\frac{Z}{z_{0\mathrm{D}}}\right)$
- none of the two limits is fully satisfactory, still the former is used in ISBA and the latter in SURFEX

Proper choice of the lowest model level

- in heterogeneous gribox, lowest model level should be placed at height where the wind speed no longer depends on local roughness, but the flow is still in equilibrium with surface (Vihma and Savijärvi 1991)

- lowest such height is called **blending height**

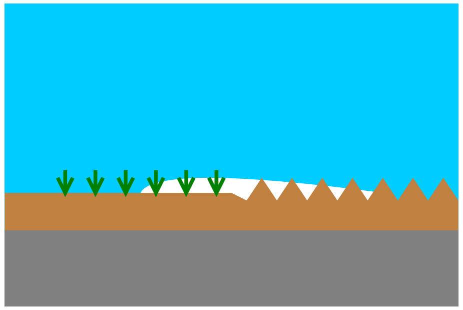


- Mason (1988) estimates blending height as $L/200$, where L is linear size of homogeneous gribox patches in the direction of wind

- for $L = 2\,\text{km}$ it gives blending height $\sim$10 m, which is height of the lowest model level in ALARO $\Rightarrow$ averaging of micrometeorological roughness at 2.3 km resolution should be safe

Roughness treatment in ISBA – found problems

- focus will be put on the snow scheme of Bazile et al. (2001), activated by setting LSNV=F, LVGSN=T
- here the new roughness treatment LZ0HSREL=T suffers from several problems:
  1. **linear roughness averaging** between snow free and snow covered parts of gridbox, incompatible with quadratic inclusion of orographic roughness
  2. missing orographic roughness for snow, compensated by **different snow fractions** in averaging albedo/emissivity and roughness
  3. reduction of snow fraction over rough surface parameterized using **effective** dynamical roughness instead of micrometeorological one



Roughness treatment in ISBA – applied fixes

- problems 2 and 3 were partially compensating, giving acceptable results but with unphysically tuned snow fraction in roughness averaging

- the new roughness treatment LZ0HSREL=T was corrected only under TOUCANS in ALARO-1, applying following fixes:
  - **quadratic roughness averaging** between snow free and snow covered parts of gridbox, as under option LSNV=T
  - orographic roughness **included** for snow
  - **unified snow fraction** in averaging albedo/emissivity and roughness
  - reduction of snow fraction over rough surface parameterized using **micrometeorological** dynamical roughness
  - **consistent use** of roughness values throughout the model physics

- new treatment combines **effective** dynamical roughness $z_{\mathrm{0D}}^{\mathrm{eff}}$ with **micrometeorological** thermal roughness $z_{\mathrm{0H}} \Rightarrow$ departure from preservation of heat coefficient C_{H}

Treatment of heat coefficient

- heat coefficient in neutrality reads (red quantities are increased due to subgrid-scale orography, $z_{0\mathrm{H}} = z_{0\mathrm{D}}/10$):

1) LZ0HSREL=F:
$$C_{\mathrm{HN}} = \frac{\kappa^2}{\ln\left(1 + \frac{Z}{z_{0\mathrm{D}}^{\mathrm{eff}}/10}\right) \ln\left(1 + \frac{Z}{z_{0\mathrm{D}}^{\mathrm{eff}}}\right)}$$

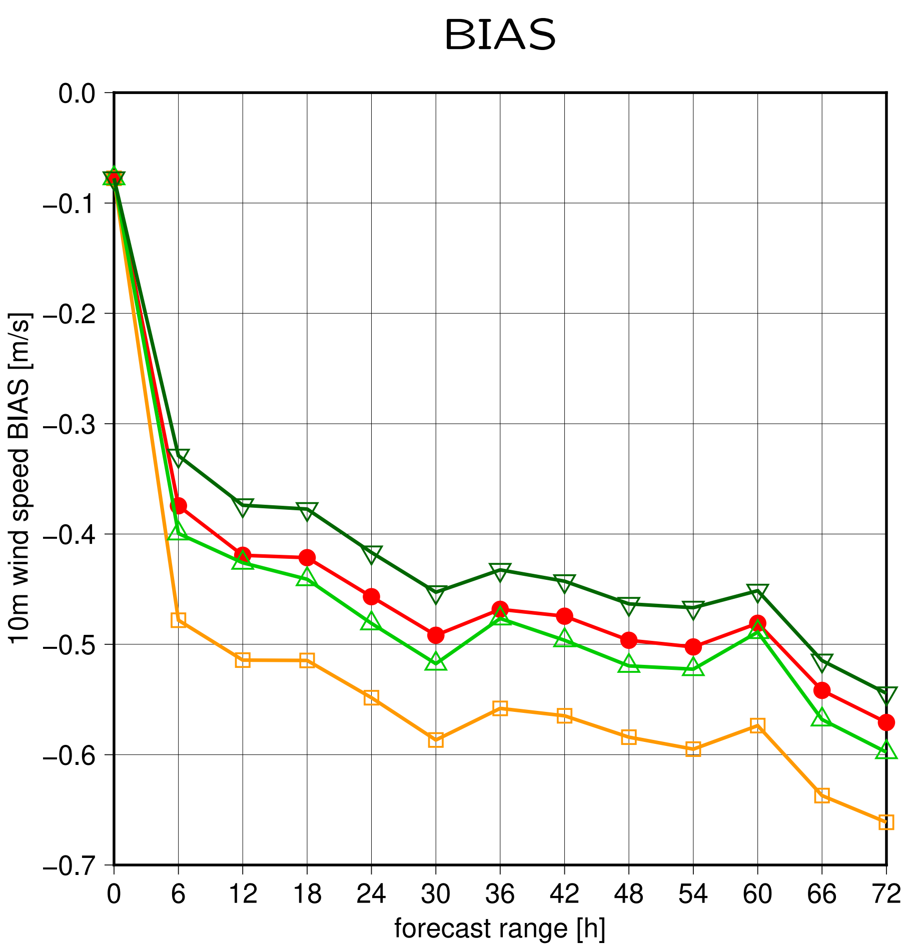
2) LZ0HSREL=T, unfixed:
$$C_{\mathrm{HN}} = \frac{\kappa^2}{\ln\left(1 + \frac{Z}{z_{0\mathrm{H}}}\right) \ln\left(1 + \frac{Z}{z_{0\mathrm{D}}}\right)}$$

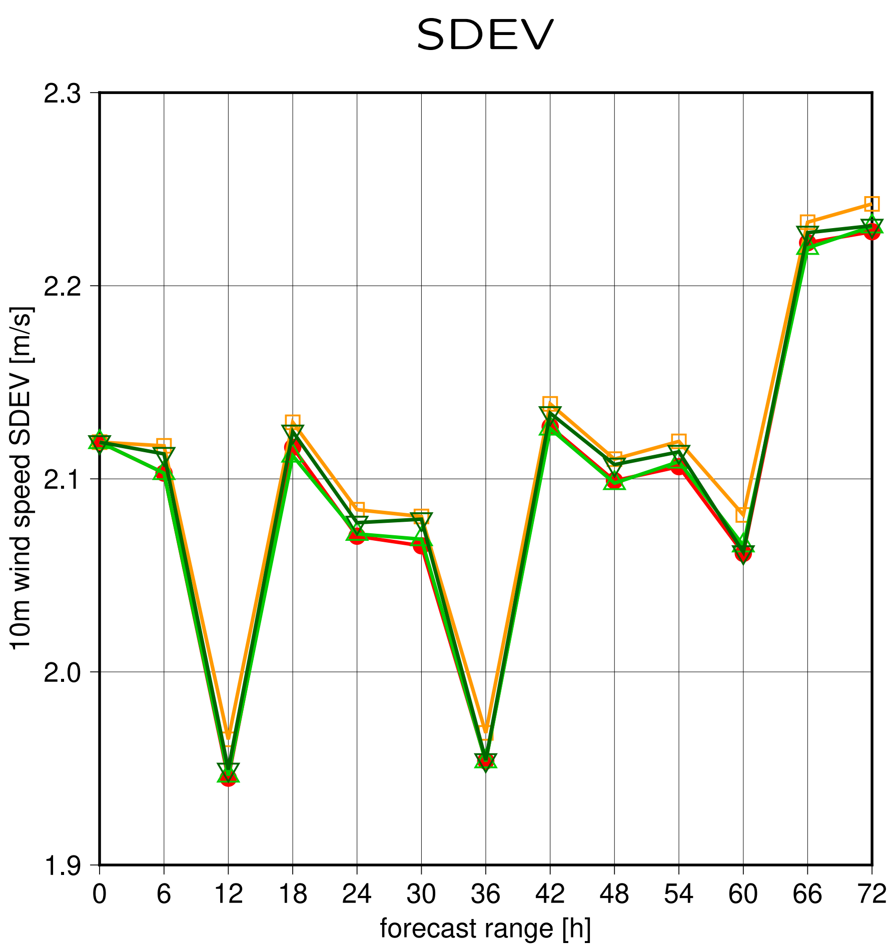
3) LZ0HSREL=T, fixed:
$$C_{\mathrm{HN}} = \frac{\kappa^2}{\ln\left(1 + \frac{Z}{z_{0\mathrm{H}}}\right) \ln\left(1 + \frac{Z}{z_{0\mathrm{D}}^{\mathrm{eff}}}\right)}$$

- choice 3) adopted in ALARO-1 is a halfway between 1) and 2), partially increasing heat coefficient C_{H} over unresolved orography
- in winter it yields slightly smaller random error of screen level quantities than the use of effective thermal roughness $z_{0\mathrm{H}}^{\mathrm{eff}} \leq z_{0\mathrm{H}}$

Gain at 4.7 km resolution – 10 m wind speed

14–31 January 2017, dynamical adaptation

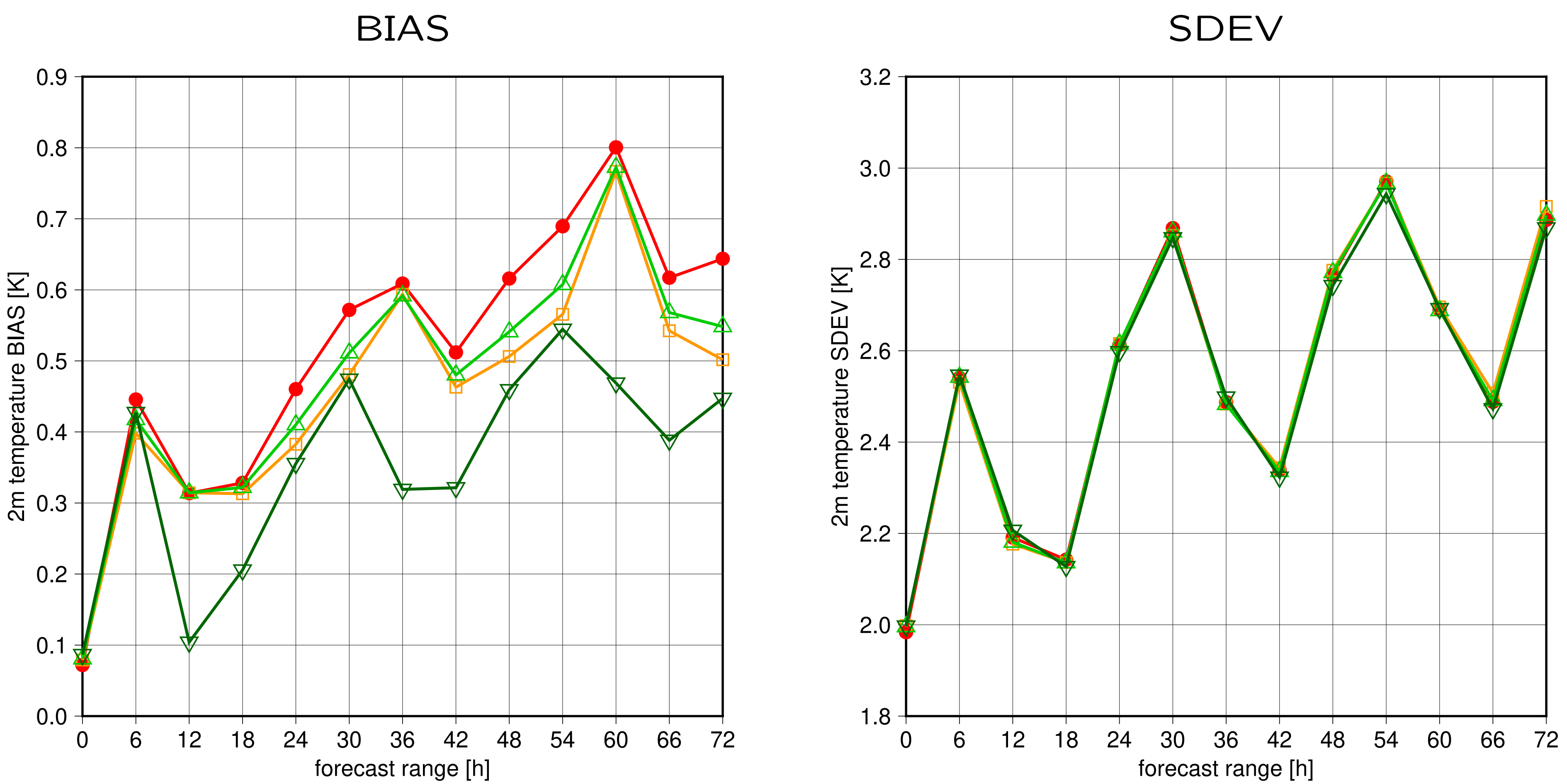




FACZ0=0.53, NLISSZ=3, LZ0HSREL=F
FACZ0=1.00, NLISSZ=1, LZ0HSREL=T, unfixed
FACZ0=0.53, NLISSZ=3, LZ0HSREL=T, unfixed
FACZ0=0.53, NLISSZ=3, LZ0HSREL=T, fixed & retuned

Gain at 4.7 km resolution – 2 m temperature

14–31 January 2017, dynamical adaptation



FACZ0=0.53, NLISSZ=3, LZ0HSREL=F

FACZ0=1.00, NLISSZ=1, LZ0HSREL=T, unfixed

FACZ0=0.53, NLISSZ=3, LZ0HSREL=T, unfixed

FACZ0=0.53, NLISSZ=3, LZ0HSREL=T, fixed & retuned

Recommended tunings

e923 settings			
configuration \ variable	LZ0THER	FACZ0	NLISSZ
ALARO-0, old ALARO-1	T	0.53	3
ARPEGE & AROME equivalent	F	1.00	1
new ALARO-1	F	0.53	3

integration settings			
configuration \ variable	LZ0HSREL	WCRIN	ALRCN2
ALARO-0, old ALARO-1	F	10	0.0025
new ALARO-1	T	4–5	10

$$f_{\text{snow}}^{\text{bg}} = \frac{W_{\text{snow}}}{W_{\text{snow}} + \text{WCRIN} \cdot \left(1 + \frac{z_{\text{0D}}^{\text{nosnow}}}{\text{ALRCN2}}\right)} \qquad \text{(unified formula)}$$

$f_{\text{snow}}^{\text{bg}}$	–	snow fraction over bare ground	[1]
W_{snow}	–	snow reservoir	$[\text{kg}\cdot\text{m}^{-2}]$
$z_{\text{0D}}^{\text{nosnow}}$	–	dynamical roughness without snow	[m]

Remarks

- originally recommended setting for e923 option LZ0THER=F was FACZ0=1.00 and NLISSZ=1
- however, increased orographic roughness turned to be detrimental for 10 m wind speed, increasing its negative bias
- returning to FACZ0=0.53 and NLISSZ=3 brought wind bias almost back to values seen for LZ0THER=T
- since the smoothing of orographic roughness is done on its logarithm, mean value is diminished ⇒ using NLISSZ=1 with FACZ0≈0.40 can be considered
- additional gain in wind bias was obtained by fixing problems under option LZ0HSREL=T, overcoming reference with LZ0HSREL=F
- positive 2 m temperature bias was reduced by retuning unified snow fraction, lowering WCRIN at 4.7 km resolution from 10 to 5

Conclusions

- activation of option LZ0HSREL=T in ALARO-1 necessitated revision of recommended e923 tunings for orographic roughness
- equally important was an inspection of roughness treatment in ISBA, revealing several problems for snow
- on 4.7 km resolution, fixed and retuned option LZ0HSREL=T nicely reduces winter bias of 2 m temperature and 10 m wind speed
- it was adopted as preferred option for 2.3 km resolution, necessary (but not sufficient) for consistency with SURFEX
- at high resolution, quality of e923 orography related fields derived from GTOPO30 is questionable $\Rightarrow$ replacement by GMTED2010 is strongly desirable

Questions for thought

- is there an overlap between use of effective dynamical roughness $z_{0\mathrm{D}}^{\mathrm{eff}}$ and parameterization of form drag in subroutine ACDRAG?

- how relevant is the concept of effective thermal roughness $z_{0\mathrm{H}}^{\mathrm{eff}}$ alias no influence of subgrid-scale orography on heat coefficient C_{H}?

- is the use of Monin-Obukhov similarity theory justified for screen level interpolation of gridbox averaged quantities over complex terrain?

- what is the depth of roughness sublayer on gridbox scale, accounting for unresolved orography?