Vertical Coordinate Parameters in the COSMO-Model and GRIB

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1. Vertical Coordinate Parameters and the Reference Atmosphere

In GRIB, the vertical discretization of a model grid can be encoded by the vertical coordinate parameters. In Grib1 they are part of the *Grid Description Section (GDS)*, while in Grib2 they belong to the *Product Definition Section (PDS)*.

In the COSMO-Model (still using Grib1), not only the vertical coordinate parameters are encoded in the grid description section, but also some variables necessary to compute the reference atmosphere. When using the SLEVE coordinate, even more additional parameters are encoded as "vertical coordinate parameters", which are necessary to compute the splitting of the orography into the large-scale and small-scale components. This is not a standard encoding of vertical levels in GRIB!

The following table recalls the values that the COSMO-Model encodes together with the vertical coordinate parameters (depending on the model version and the options chosen):

`ivctype`	Type of the vertical coordinate (values $\geq$ 100 indicate the new reference atmosphere) 1: Pressure based hybrid coordinate η 2: Height based hybrid coordinate μ 3: Height based hybrid SLEVE coordinate μ_s
`ke`	Number of vertical levels
`p0sl, t0sl`	Reference pressure and temperature on sea-level
`vcflat`	Coordinate value where system changes back to z-levels
`dt0lp`	d (t0) / d (ln p0) ("old" reference atmosphere)
`delta_t`	temperature difference between sea level and stratosphere ("new" reference atmosphere)
`h_scal`	scale height ("new" reference atmosphere)
`bv_ref`	for constant Brunt-Väisala reference atmosphere (idealized cases only)
`svc1, svc2, nfltvc`	decay rates and number of filtering steps for splitting the orography for the SLEVE coordinate
`vcoord`	list of the vertical parameters

Because of changes in the COSMO-Model (adding the SLEVE coordinate; adding a new reference atmosphere), the way, how these values are encoded, is not consistent over the years. There are some IF-clauses now in the code to read and decode old data properly. With the introduction of GRIB2 and the use of the ECMWF GRIB-API, the COSMO-Model should try to use a standard encoding of the vertical coordinate. But the biggest problem is, that most of these values are not related to the vertical grid and should be coded elsewhere.

In the following sections we try to describe the problem with encoding the vertical grid in the Grib code in more detail (Section 2). We also will give more information about the reference atmosphere (Section 3).

It is not intended to do changes in the Grib1 (although we have to see how GRIB-API can deal with the actual situation), but the above mentioned problems should be solved, when introducing Grib2. Because of the Interoperability-Programme, where Grib2 data should be provided soon, there is an immediate need to discuss some solutions.

2. Encoding the vertical grid

From the GRIB Standard

First, only the vertical coordinate parameters themselves should be encoded in the appropriate section of the Grib code. But the list of vertical coordinate parameters provided by the COSMO-Model cannot be interpreted by the standard GRIB up to now. See the notes on coordinate values from the GRIB(2) definition (from *Manual on Codes - International Codes: I.2 - GRIB Reg - page 7*):

(1) Coordinate values are intended to document the vertical discretization associated with model data on hybrid coordinate vertical levels. A number of zero in octets 6-7 indicates that no such values are present. Otherwise the number corresponds to the whole set of values.

(2) Hybrid systems, in this context, employ a means of representing vertical coordinates in terms of a mathematical combination of pressure and sigma coordinates. When used in conjunction with a surface pressure field and an appropriate mathematical expression, the vertical coordinate parameters may be used to interpret the hybrid vertical coordinate.

(3) Hybrid coordinate values, if present, should be encoded in IEEE 32-bit floating point format. They are intended to be encoded as pairs.

This means, the standard GRIB code (still) has a vertical coordinate system in mind, that is used in hydrostatic models, where the pressure on the vertical levels could be computed for every grid point ij by

$$p_{ijk} = a_k + b_k \cdot p_{s_{ij}}, \quad k = 1, \ldots, ke. \tag{1}$$

The a_k and b_k are the pairs of vertical coordinate parameters and p_s is the surface pressure. The height of the vertical levels is then computed from p_{ijk} using the hydrostatic equation.

But what the COSMO-Model provides, is a (single) list of vertical coordinate parameters σ_k (sometimes in the documentation also called η_k) together with additional values related to the reference atmosphere.

Type of vertical levels

In Grib1, different type of vertical levels can be specified by setting the *Indicator of type of level* (see Grib1 Code Table 3). The numbers 109 and 110 indicate a hybrid system. In the COSMO-Model 110 is used to specify the full levels (or the layers) and with 109 the half levels (or surfaces between layers) are determined.

To identify the type of levels in Grib2, a value from Grib2 Code Table 4.5 has to be chosen. Up to now the value 105 ("hybrid levels") is used for both, the half and the full levels. In Grib2 this value has to be chosen for the so-called *Type of first fixed surface* and the *Type of second fixed surface* in the Product Definition Templates 4.X. To specify both values means, that the product is valid for a whole layer, which has an upper (the first) and a lower (the second) surface (in COSMO terms: the full levels). If only the type of the first fixed surface is specified, the product is valid only for this surface (in COSMO terms: the half levels).

In September 2009, ECMWF made a proposal to WMO and suggested, not to use the number 105 anymore, but to distinguish between height based and pressure based hybrid systems. Usage of the following 2 numbers is proposed now:

118: Height based hybrid system:
Coordinate values a_k and b_k should be given, where the height of any grid point ij on (half) levels can be computed by

$$hhl_{ijk} = a_k + b_k \cdot hsurf_{ij}, \quad k = 1, \dots, ke. \tag{2}$$

where $hsurf$ is the height of the orography (in meter).

119: Pressure based hybrid system:
Coordinate values a_k and b_k should be given, where the full pressure of any grid point ij on (half) levels can be computed by Eq. (1).

The situation in the COSMO-Model

When developing the COSMO-Model, it was decided to encode the σ_k-values because several vertical coordinate types could be coded in this way. These types are denoted by `ivctype`. But this approach is not reflected in the existing GRIB standard(s).

In the following, it is briefly described, how the vertical grid is derived for the different COSMO vertical coordinate types and whether (and how) they can fit into the existing Grib standard(s). In the COSMO-Model, the computations are done by the routines `reference_atmosphere` and `reference_atmosphere_2`, resp.

(a) Pressure based hybrid coordinate η (`ivctype=1`)

This vertical coordinate type is similar to the pressure based systems used in hydrostatic models. A formula similar to (1) is used to compute the pressure on the vertical levels.

But instead of using the actual surface pressure, a constant reference surface pressure p_s^0 is taken. Therefore, the vertical grid is not varying, but fixed in space and time. From the σ_k, a corresponding set of vertical coordinate parameters a_k and b_k are computed by

$$
\begin{aligned}
a_k &= \begin{cases} \sigma_k \cdot p_{sl}^0 & \text{if} \quad \sigma_k \le \sigma_{flat}, \\ \sigma_{flat} \cdot p_{sl}^0 \cdot \frac{1.0-\sigma_k}{1.0-\sigma_{flat}} & \text{if} \quad \sigma_k > \sigma_{flat} \end{cases} \\
b_k &= \begin{cases} 0 & \text{if} \quad \sigma_k \le \sigma_{flat}, \\ \frac{\sigma_k-\sigma_{flat}}{1.0-\sigma_{flat}} & \text{if} \quad \sigma_k > \sigma_{flat} \end{cases}
\end{aligned} \tag{3}
$$

Here, the COSMO vertical coordinate parameters are $\sigma_1, \ldots, \sigma_{ke+1}$, which in the program are called $\texttt{vcoord}(1), \ldots, \texttt{vcoord}(\texttt{ke}+1)$. For every k it holds $\sigma_k \in [0,1]$. p_{sl}^0 is the reference pressure on sea-level and σ_{flat} is the σ-value, where the vertical levels change back to the z-system (in the program denoted as `vcflat`. The threedimensional reference pressure (the so-called reference atmosphere) then is given for every grid point ij by

$$p_{ijk}^0 = a_k + b_k \cdot p_{s_{ij}}^0, \quad k = 1, \ldots, ke. \tag{4}$$

How the reference surface pressure p_s^0 is computed, depends on the reference atmosphere chosen and the additional parameters like p_{sl}^0, t_{sl}^0, etc. Also, the computation of the height of the half levels then depends on the chosen reference atmosphere.

If this type of vertical coordinate should be maintained, an extension to the GRIB2 standard has to be proposed to WMO:

- A new "appropriate number" has to be chosen in Grib2 Code Table 4.5:
  nnn: Reference pressure based hybrid system
- A new field "Reference Pressure" has to be defined in Discipline 0 (Meteorological Products), Category 3 (Mass):
  mmm: Reference Pressure
- To identify the reference atmosphere chosen and the settings of the free parameters, these parameters have to be encoded in some GRIB section of this product (see Sect. 3 for details).

While Eq. (4) to compute the threedimensional reference pressure is rather straightforward, the algorithms to compute the height of the levels for the different reference atmospheres are not. Hydrostatic models use the hydrostatic equation, but more complex formulas have to be used in the COSMO-Model.

Therefore we give the following

Recommendation:
The vertical coordinate type 1 of the COSMO-Model should be eliminated. It will be maintained in the code just to properly read and decode old data, but from a certain date on it should not be possible to produce data for `ivctype=1` any more. Especially when using Grib2, this vertical coordinate type is not used any more.

(b) Height based hybrid coordinate μ (`ivctype=2`)

The height based hybrid coordinate μ fits to the proposed *type of fixed surfaces* 118. The COSMO vertical coordinate parameters $\sigma_1, \ldots, \sigma_{ke+1}$ now give the height above mean sea level in meters. The other set of vertical coordinate parameters a_k and b_k are computed by:

$$
\begin{aligned}
a_k &= \sigma_k \\
b_k &= \begin{cases} 0 & \text{if} \quad \sigma_k \geq \sigma_{flat}, \\ \frac{\sigma_{flat}-\sigma_k}{\sigma_{flat}} & \text{if} \quad \sigma_k < \sigma_{flat} \end{cases}
\end{aligned}
\tag{5}
$$

where σ_{flat} again is the σ-value, where the vertical levels change back to the z-system.

With the a_k and b_k, the height of the (half) levels can be computed for every grid point ij by Eq. (2):

$$
hhl_{ijk} = a_k + b_k \cdot hsurf_{ij}, \quad k = 1, \ldots, ke.
$$

Here, $hsurf$ is the height of the orography in meter. In the COSMO-Model the height of the full levels just is the arithmetic mean between the height of the half levels:

$$
\begin{aligned}
hfl_{ijk} &= \frac{1}{2} \cdot (hhl_{ijk} + hhl_{ijk+1}) \\
&= \frac{1}{2} \cdot (a_k + a_{k+1}) + \frac{1}{2} \cdot (b_k + b_{k+1}) \cdot hsurf_{ij}. \quad k = 1, \ldots, ke
\end{aligned}
\tag{6}
$$

In this case, the computation of the vertical grid uses the Eq. (2), but now the computation of the threedimensional reference pressure p^0_{ijk} is more complicated (for both types of reference atmospheres).

But usage of the *type of fixed surfaces* 118 is now straightforward for `ivctype=2`. Instead of encoding the σ_k-values, the pairs of a_k and b_k have to be encoded as the vertical coordinate parameters.

How the additional parameters necessary for the reference atmosphere can be encoded is discussed in Sect. 3.

Recommendation:
The vertical coordinate type 2 of the COSMO-Model can further be used and can be coded in Grib 2 with vertical coordinate type 118. As vertical coordinate parameters, the values for a_k and b_k from Eq. (5) have to be given. But Namelist Input for the INT2LM still will be the σ_k-values.

(c) Height based hybrid SLEVE coordinate μ_s (`ivctype=3`)

The height based hybrid SLEVE coordinate, suggested by Schär et al., produces a smooth computational mesh at mid and upper levels. Similar to the definition of the normal height based hybrid coordinate, it takes the values $\mu_s = 0$ at the surface and $\mu_s = z_T$ at the top (where z_T is the height of the top in meters). Using the basic SLEVE coordinate, the height of the half levels can be computed by:

$$hhl_{ijk} = a_k + b_k^1 \cdot hsurf_{ij}^1 + b_k^2 \cdot hsurf_{ij}^2, \tag{7}$$

where $hsurf^1$ and $hsurf^2$ denote the large-scale and the small-scale components of the topography $hsurf$, which satisfy the relation

$$hsurf_{ij} = hsurf_{ij}^1 + hsurf_{ij}^2. \tag{8}$$

The vertical coordinate parameters are given by:

$$\begin{aligned} a_k &= \sigma_k \\ b_k^1 &= \begin{cases} 0 & \text{if} \quad \sigma_k \geq \sigma_{flat}, \\ \frac{\sinh\{(\sigma_{flat}-\sigma_k)/svc_1\}}{\sinh\{\sigma_{flat}/svc_1\}} & \text{if} \quad \sigma_k < \sigma_{flat} \end{cases} \\ b_k^2 &= \begin{cases} 0 & \text{if} \quad \sigma_k \geq \sigma_{flat}, \\ \frac{\sinh\{(\sigma_{flat}-\sigma_k)/svc_2\}}{\sinh\{\sigma_{flat}/svc_2\}} & \text{if} \quad \sigma_k < \sigma_{flat} \end{cases} \end{aligned} \tag{9}$$

where σ_{flat} again is the σ-value, where the vertical levels change back to the z-system and svc_1, svc_2 define the vertical decay rates of the respective topography component.

Note, that other variants of the SLEVE coordinate (SLEVE2) use different construction algorithms.

This vertical coordinate type does not fit into the existing Grib definitions. And it can already be foreseen that there will be other vertical grids with different construction algorithms.

Therefore a new type of level should be proposed to WMO:

Recommendation:
A new vertical coordinate type should be defined in Code Table 4.5 (*Fixed surface types and units*):

150: general vertical height coordinate:
The general vertical height coordinate is not specified by vertical coordinate parameters but by providing a 3D (Grib2) field, that specifies the height of every model grid point in meters (i.e. the field with discipline=0, category=3 and parameter=6).

In this case, no vertical coordinate values are given for the "optional list of coordinate values", but some numbers that define the vertical grid (defined by originating centre). 2 numbers should be given at least:

1: The number of vertical levels `NLEV`

2: A number identifying the special vertical grid used `NGRID`

Short Summary

- A new "vertical coordinate type (150)" shall be proposed to WMO for Grib2 Code Table 4.5., the *generalized vertical height coordinate*.
- The vertical coordinate type `ivctype=1` should not be used any more (altough it can be coded with the new type). It will be maintained, however, to decode historical data properly.
- Model data with ivctype=2 can be encoded in Grib2 either with vertical coordinate type 118 and specifying the vertical coordinate values a_k and b_k or with the new vertical coordinate type 150 and specifying the height of the model (half) levels.

3. Providing Information about the Reference Atmosphere

If the changes for encoding the vertical coordinate parameters proposed in the last section are implemented, the information about the reference atmosphere is lost in the first instance. This information (the reference atmosphere parameters p^0_{sl}, t^0_{sl}, etc.) is necessary, if the pressure deviation p' (field `pp` in the COSMO-Model and the INT2LM) has to be processed, because then the threedimensional reference pressure p^0 has to be computed to get the full pressure p. The pressure deviation has been chosen as the transfer parameter between the INT2LM and the COSMO-Model and also between the assimilation cycle and the forecast, because it minimizes the loss in precision because of the Grib packing.

To maintain the information about the reference atmosphere, there are the following possibilities:

1. The reference pressure p^0 is introduced as a new field in discipline 0, category 3. The pressure deviation already exists in the local use area (parameter number 192). But even then it would be desirable to know the reference atmosphere parameters, with which a special p^0 has been computed.
2. The reference atmosphere parameters p^0_{sl}, t^0_{sl}, etc. are encoded in the local section of the Grib. For DWD this section already contains some information about the Grib records, which were encoded in local use areas of Grib1. It is important to encode these real values with a rather high precision.
3. An extension of the Product Definition Section for (optional) "Reference Atmosphere Parameters" could be proposed to WMO.

At the moment, the second option seems to be the most practical one. Therefore, the following procedure is proposed:

- Encoding of the vertical coordinate parameters is done as proposed in Sect. 2 (encode the a_k and b_k).
- Only when encoding the reference pressure p^0 or the pressure deviation p' the reference atmosphere parameters are encoded in the Local Section (Sect. 2) of Grib2.

- Forecast output of the COSMO-Model always contains the full pressure, so there is no need to compute the reference atmosphere.
- The pressure deviation is only used as a transfer parameter between INT2LM and the COSMO-Model or the assimilation cylce and the COSMO-Model forecasts.
- If assimilation products (including p') are distributed to customers, they have to be aware how they can compute the reference atmosphere. Alternatively, the full threedimensional reference pressure p^0 can be distributed in addition.
- Encoding the reference atmosphere parameters together with the vertical coordinate parameters σ_k and the use of the vertical coordinate type `ivctype=1` will be abolished in Grib2.