

# Technical Memo

## 852

### **An overview of Convective Available Potential Energy and Convective Inhibition provided by NWP models for operational forecasting**

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## Abstract

This document presents a review of the computation of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) from NWP model data conducted for ECMWF by the European Severe Storms Laboratory (ESSL). Various ways of computing CAPE and CIN are illustrated in selected meteorological situations. The most important differences arise from the choice of the air parcel for which CAPE and CIN are calculated, but other assumptions are also important. The forecaster survey at the ESSL Testbed 2019 among 38 participants, suggests that forecasters prefer using both CAPE/CIN for a near-surface mixed-layer parcel and for the most unstable parcel in the profile, but not for a parcel originating from the lowest model level. CAPE and CIN provided by the Integrated Forecasting system (IFS) are compared to those provided in other operational NWP models (ARPEGE, AROME, UM, HiRLAM, ICON, COSMO). The implemented calculations differ regarding their intended use (for forecasters, model-internal use), choice of parcel (most unstable only, or also for a near-surface mixed-layer), whether entrainment is assumed in the parcel, whether the process is reversible or pseudo-adiabatic ascent, and whether the latent heat of freezing and disposition are accounted for. ESSL provided a code of the computation of various types of CAPE and CIN which was tested with the IFS model data. Results of the testing have been summarised and ESSL provided recommendations on the computation of CAPE and CIN and their subsequent use. CAPE and CIN for the near-surface 50 hPa mixed-layer parcel and for the most unstable parcel contain some independent information that is valuable to forecasters. In parcel calculations, it is recommended to implement pseudo-adiabatic ascent to ensure that an underestimation of instability is prevented (which could occur if reversible ascent is implemented) and without accounting for latent heat of freezing and disposition. Future ECMWF's plans of revising the CAPE and CIN model output are outlined at the end of this paper.

## 1 Introduction

Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) are two meteorological parameters widely used for forecasting convection. There are large variations though in the practical computation of these indices depending on the air parcel considered and physical processes accounted for during the parcel's ascent. Like other modelling centres, ECMWF provides CAPE and CIN as a model output from its Integrated Forecasting System (IFS). The computation of CAPE and CIN in the IFS is performed with some approximations based on computational efficiency considerations as well and this raises questions on their interpretation and comparison to the output from other Numerical Weather Prediction (NWP) models. Following feedback from its Member States, ECMWF commissioned an expert review of CAPE and CIN computation in NWP models and forecasters' experience of using model output. This study was conducted by the European Severe Storms Laboratory (ESSL) and the results are presented here. These results will ensure that revisions to ECMWF CAPE and CIN computational practises will harmonise its output to other NWP models for better comparison and easier interpretation by forecasters.

Various ways of computing CAPE and CIN are illustrated in selected meteorological situations. The most important differences result from the choice of the air parcel for which CAPE and CIN are calculated, but other assumptions are also important. A survey at the ESSL Testbed 2019 among 38 forecasters, suggests that they prefer using both CAPE/CIN for a near-surface mixed-layer parcel and for the most unstable parcel in the profile, but not for a parcel originating from the lowest model level.

A survey among NWP experts at four ECMWF member states (Germany: DWD, UK: Met Office, France: Météo-France, the Netherlands: KNMI) reveals that important differences exist between the ways that CAPE and CIN calculations are implemented in operationally used NWP models (ARPEGE,

AROME, UM, HiRLAM, ICON, COSMO). The implemented calculations differ regarding their intended use (for forecasters, model-internal use), choice of parcel (most unstable only, or also for a near-surface mixed-layer), whether entrainment is assumed in the parcel, whether the process is reversible or pseudo-adiabatic ascent, and whether the latent heat of freezing and disposition are accounted for.

Finally, recommendations for the most useful types of CAPE and CIN in the IFS and their computation are formulated based on the collected information from NWP experts and the forecasters' feedback. At the end of this paper future ECMWF's plans of revising CAPE and CIN output from the IFS are outlined.

## 2 Convective Available Potential Energy and Convective Inhibition

### 2.1 Parcel theory

CAPE and CIN are two parameters that can be derived from vertical profiles of temperature and humidity throughout the troposphere that have either been measured or modelled. The parameters are widely used in the prediction of convective storms, as they describe, respectively, the specific potential energy of air in the lower troposphere that is potentially released in convective storms, and which must be overcome before the energy release takes place. As such, they are physical quantities with a direct physical interpretation, which set them apart from the plethora of convective indices that only relate to the physics of convection in an indirect or convoluted way (see Haklander and Van Delden 2003; Kunz 2007).

CAPE and CIN are both vertical integrals of the thermal buoyancy  $B^1$  of a hypothetical air parcel that is lifted from its original vertical position. The computation can be visualized on a thermodynamic diagram, for instance a Skew-T-log-p diagram (Figure 1). They can be expressed as (e.g., Markowski and Richardson, 2010):

$$CAPE = \int_{LFC}^{EL} B \, dz \approx \int_{LFC}^{EL} \frac{T_{v,parcel} - T_{v,env}}{\bar{T}_v} g \, dz$$

and

$$CIN = - \int_{surface}^{LFC} B \, dz \approx - \int_{surface}^{LFC} \frac{T_{v,parcel} - T_{v,env}}{\bar{T}_v} g \, dz$$

The CAPE integration starts at the Level of Free Convection (LFC), the first level above the Lifted Condensation Level (LCL), where a parcel obtains positive buoyancy and continues until the level where it ceases to be buoyant, the Equilibrium Level (EL), (or Level of Neutral Buoyancy, LNB). The CIN integration starts at the surface and continues until the LFC.

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<sup>1</sup> Thermal buoyancy is buoyancy purely due to density differences, and we will hereafter refer to it as buoyancy. A more complete definition of buoyancy that includes the effects of pressure perturbations is given by (Doswell and Markowski 2004).

CAPE gives a forecaster an indication of the vigour of the updrafts in the convective storms, and a theoretical maximum updraft speed can be calculated using  $W_{max} = \sqrt{2 CAPE}$ . CIN can in a similar way be used to estimate initial upward speed a thermal must have to reach its LFC. Such values must not be taken literally as parcel theory is a great oversimplification of convection: parcels will entrain and detrain air to and from their environment, processes that are not accounted for in parcel theory. Furthermore, the effects of both static and dynamic pressure perturbations are not taken into account, which often act to counteract convective updrafts, although the dynamic perturbation pressure can amplify vertical speed in supercell convection in strong vertical wind shear.

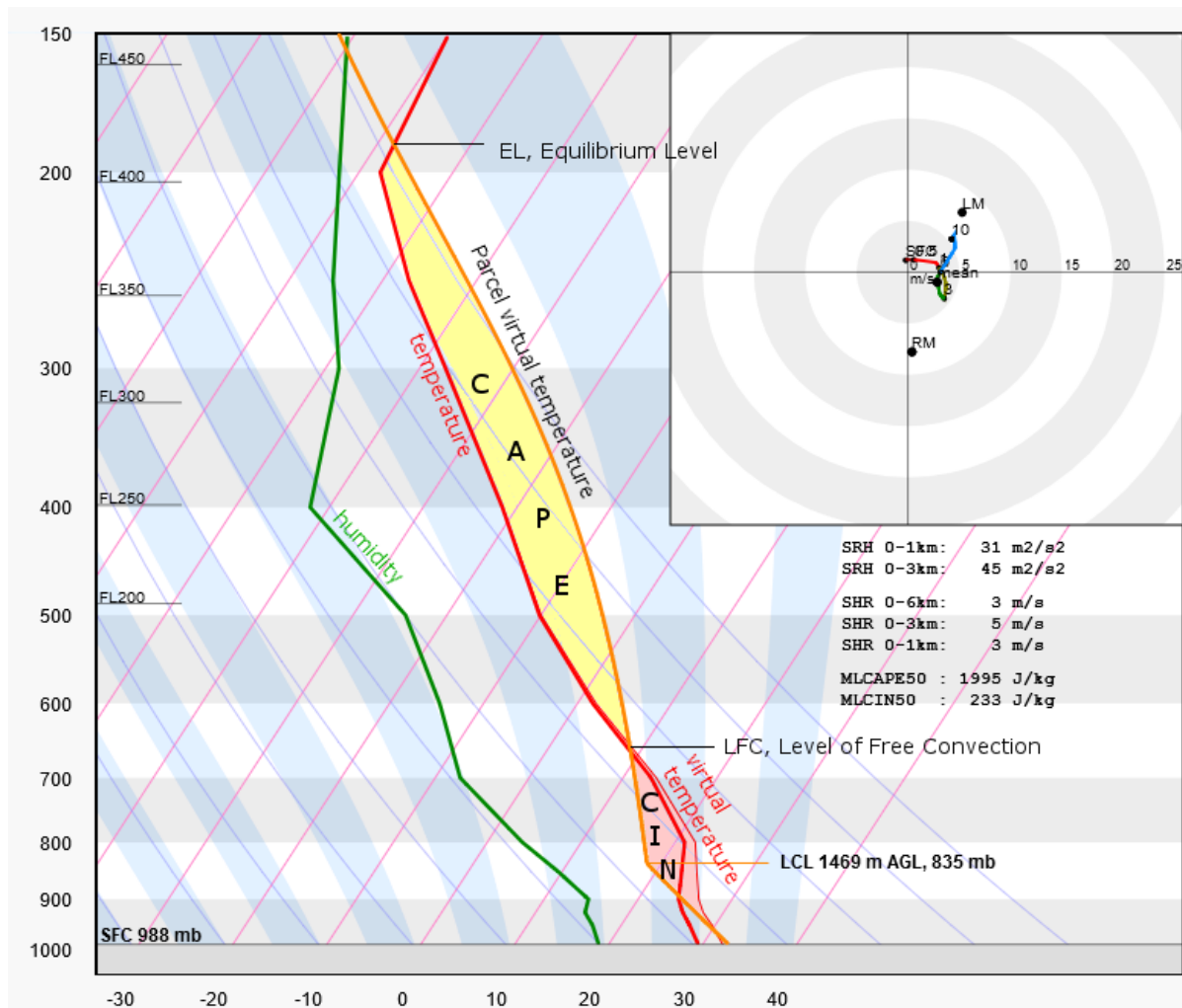


Figure 1. Skew-T-log-p diagram illustrating a number of key parameters for forecasting (severe) convective storms.

## 2.2 The choice of the parcel

The magnitude of CAPE and CIN strongly depend on the choice of the parcel that is lifted. This is where many differences exist between the way operational NWP centres calculate CAPE.

Common choices for the parcel are:

- a 50 hPa mixed-layer parcel, which is lifted from the surface, having the potential temperature and the water vapour mixing ratio of the air in the lowest 50 hPa above the surface. CAPE and CIN calculated for this parcel are called 50 hPa mixed-layer CAPE/CIN, or (MLCAPE50, MLCIN50);
- a 100 hPa mixed-layer parcel, which is lifted from the surface, having the potential temperature and the water vapour mixing ratio of the air in the lowest 100 hPa above the surface. CAPE and CIN calculated for this parcel are called 100 hPa mixed-layer CAPE/CIN, or (MLCAPE100, MLCIN100);
- the parcel that yields the highest CAPE, i.e. the most unstable CAPE or MUCAPE;
- a surface-based parcel, i.e. the parcel that starts at the earth's surface with the temperature and humidity measured or forecast at 2 m Above Ground Level (AGL). The resulting CAPE and CIN are called surface-based CAPE (SBCAPE) and surface-based CIN (SBCIN).

For forecasting convective storms, it is reasonable to aim for the parcel that is most representative of the mixture of air entering into the base of a convective updraught. Craven, Jewell and Brooks (2002) have demonstrated that the observed condensation level of convective clouds corresponds best to that of a mixed-layer parcel. Moreover, it would be difficult to assume that the air flowing into a storm originates exclusively from the lowest few metres of the boundary layer.

Because strong gradients of temperature and humidity exist in the lowest metres of a turbulent planetary boundary layer over a heated surface, SBCAPE/SBCIN and MLCAPE/MLCIN can differ quite significantly. Figure 2 demonstrates this: in this late afternoon forecast charts, MLCAPE is lower than SBCAPE. The deeper the mixing layer, the lower the resulting CAPE.

Figure 2 also shows the CAPE and CIN as implemented in IFS cycle 46r1 "IFS CAPE". The CIN from the IFS should be ignored, as a known problem that is being solved, affects this field. It is noteworthy that the IFS CAPE is even lower than the 100 hPa CAPE: for example, central and eastern Croatia exhibits sizeable SB and MLCAPE, but no IFS CAPE.

In a marine boundary layer (Figure 3 and Figure 4), a shallow stable layer may form near the surface whenever a hot air mass blows over a slightly cooler sea surface. In that case, the stable layer may become very humid with a dew point temperature approaching the sea surface temperature, which often leads to high surface-based CAPE. This CAPE is however not relevant for convective storm forecasting, as it is both highly capped (CIN is high) and representative of a layer that is too shallow to constitute a storm's inflow layer.

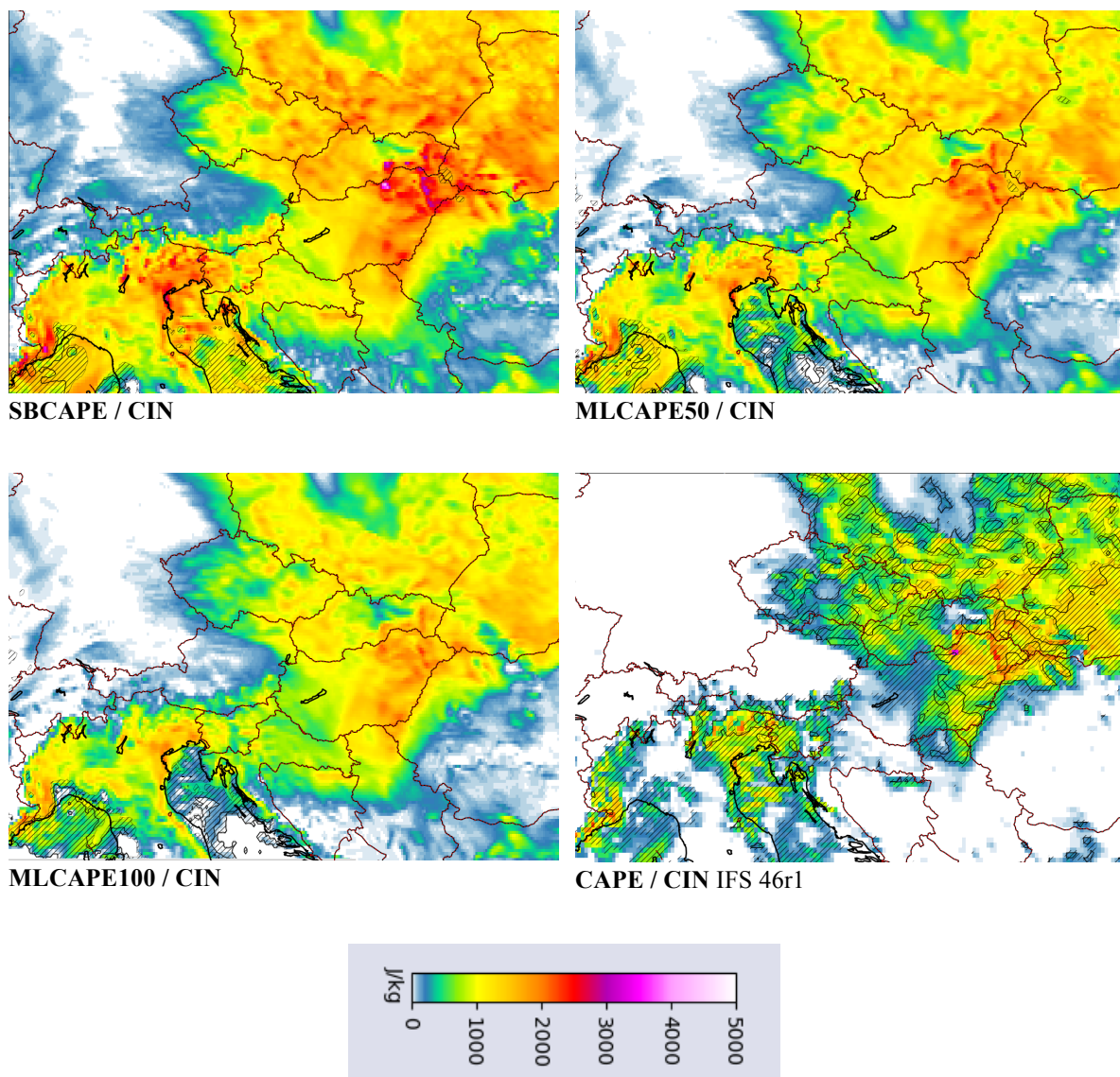


Figure 2. CAPE (colour scale) and CIN (hatched areas where  $CIN > 50 \text{ J/kg}$ , contour at  $CIN = 100 \text{ J/kg}$ ) forecast for 30 July 2019 15 UTC (+39 h), calculated for a surface-based parcel (left top), 50 hPa mixed-layer parcel (right top), 100 hPa mixed-layer parcel (left bottom), and as implemented in the ECMWF IFS cycle 46r1 (right bottom).

Most unstable CAPE has an important use in cases where convection is not fed from air right above the earth's surface, but instead from a higher level. Such situations occur often in nocturnal convection or whenever air present at the surface is cooler and/or drier than at greater altitudes. A pronounced case in early June 2019 illustrates this (Figure 5 and Figure 6). In this case, severe weather including large hail and severe winds gusts occurred across the central and west Netherlands, even though no surface-based instability was present. The full extent of the zone with instability from an elevated layer (near 850 hPa) was depicted well in the MUCAPE field, less so in the IFS CAPE field, but not in the MLCAPE or SBCAPE fields.

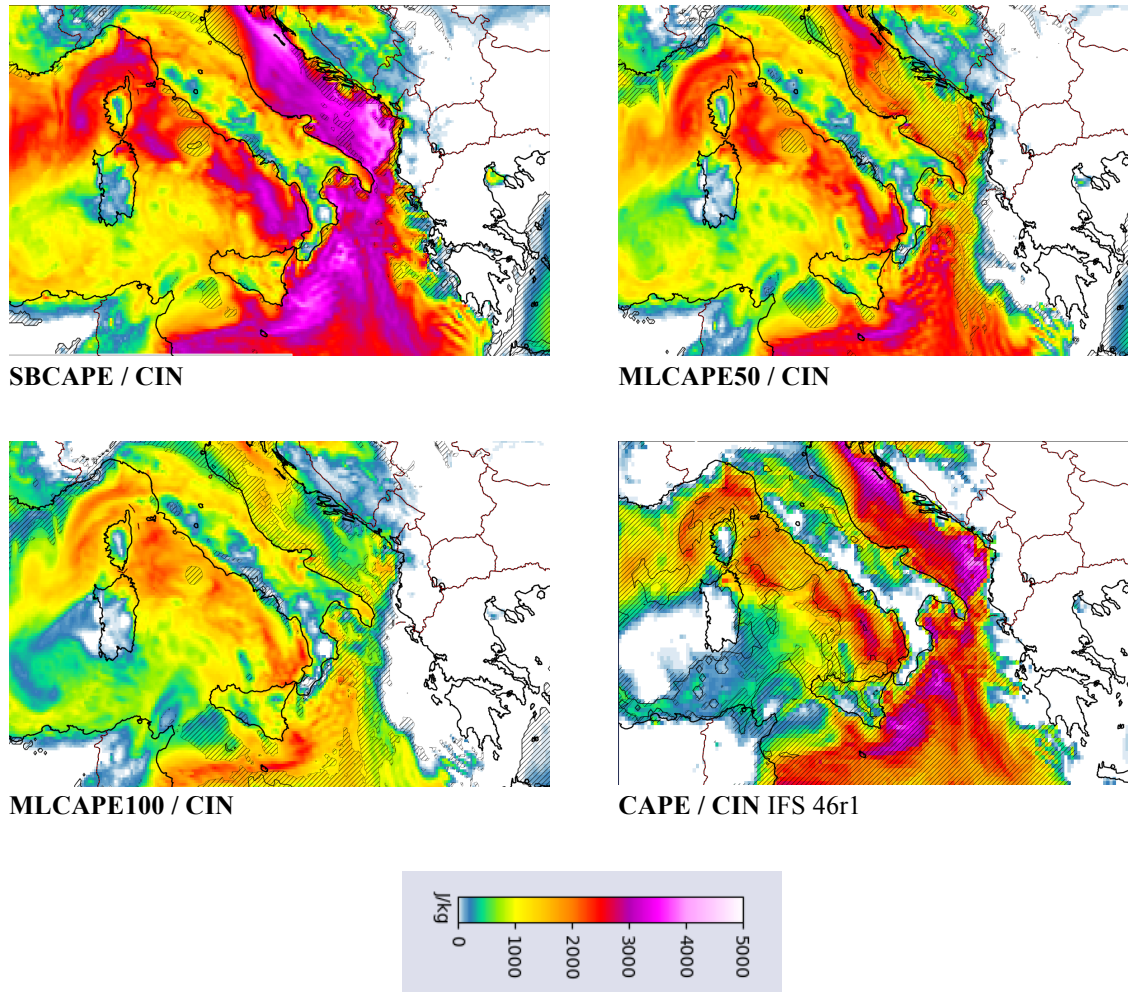


Figure 3. As Figure 2, but for 29 August 2019 09 UTC (+ 09 h).

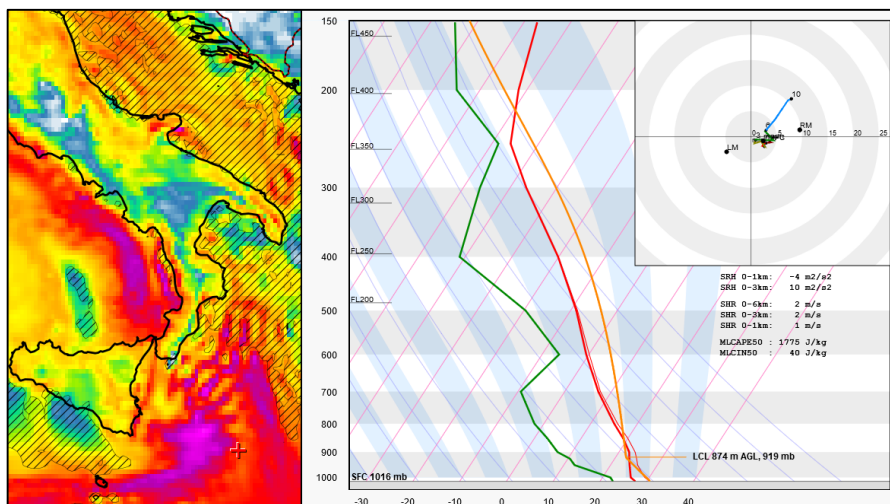


Figure 4. Forecast model sounding (using pressure-level data only) at the location marked by a cross in the western Ionian Sea (on 29 August 2019 09 UTC (+09 h)).



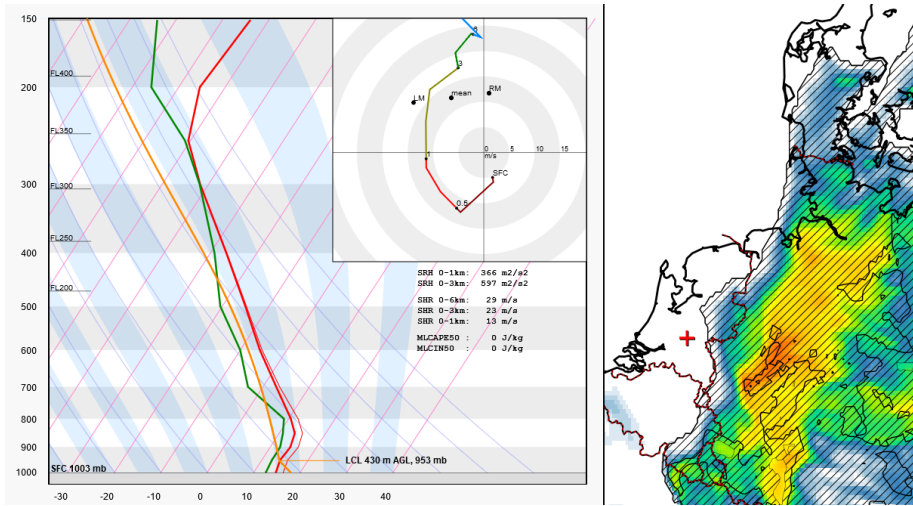


Figure 5. Forecast sounding (left; as in Figure 4) and SBCAPE and CIN (as in Figure 2) for 5 June 2019 21 UTC (+ 09 h), showing considerable elevated instability from near 850 hPa in absence of surface-based instability.

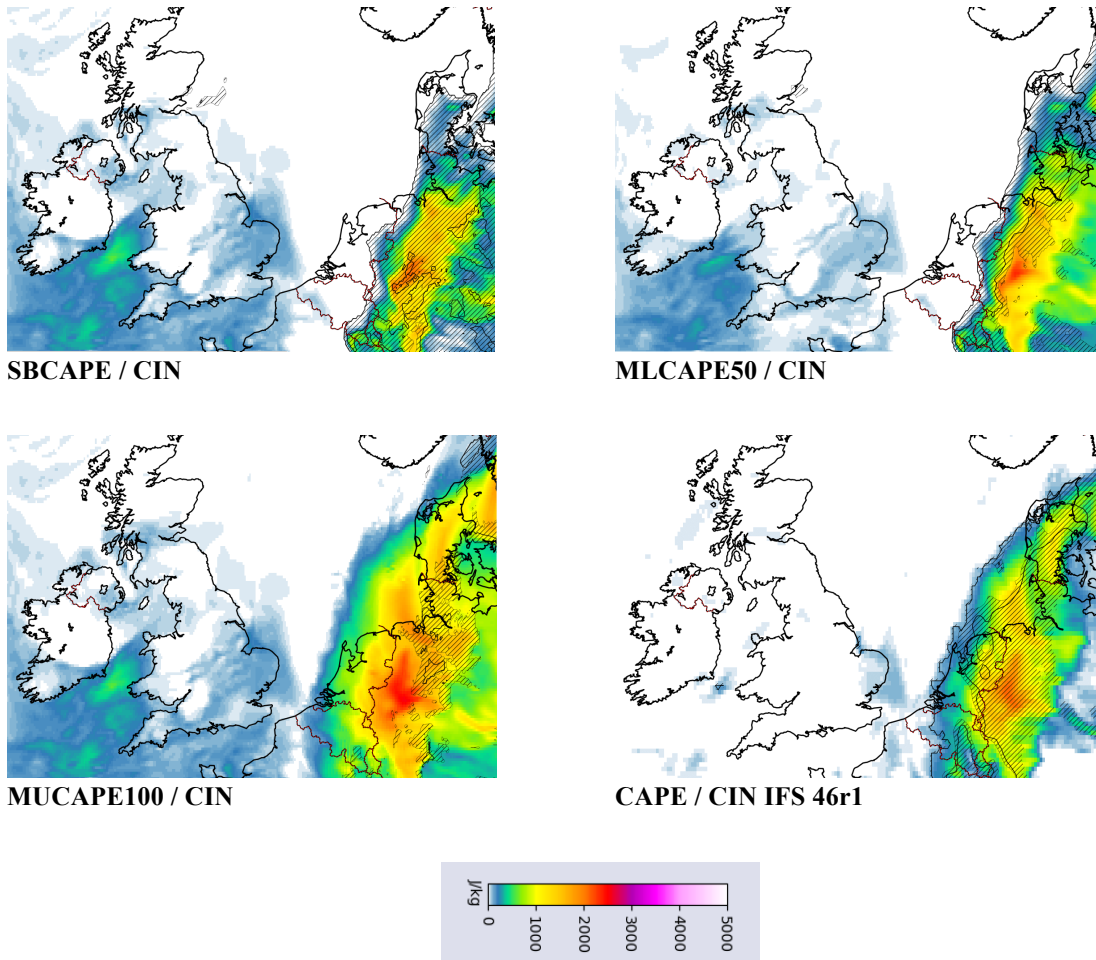


Figure 6. As Figure 2, but for 5 June 2019 21 UTC (+ 09 h).

ESSL has proposed a visualization that combines MUCAPE (in contours) with MLCAPE50 (shaded) and MUCIN (hatching) that has become popular at the Testbed. It is displayed for the above case of 5 June 2019 in Figure 7.

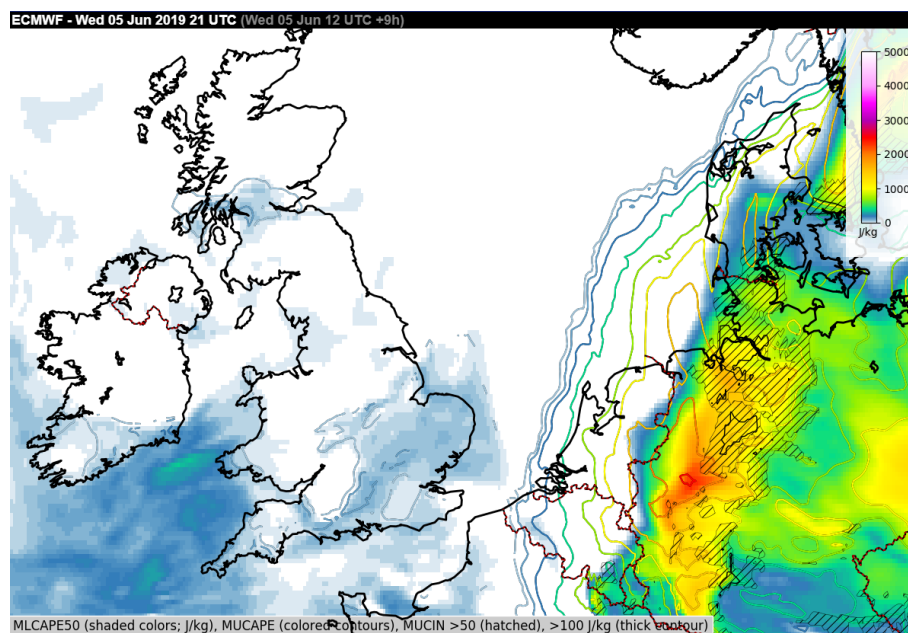


Figure 7. Visualization combining MUCAPE (contours), MLCAPE50 (shaded), and MUCIN (hatched), that has become popular at the ESSL Testbed.

### 3 Survey among forecasters attending the ESSL Testbed

ESSL has asked all participants (38 persons) to the ESSL Testbed 2019 to answer a short questionnaire about their use and knowledge of the parameters CAPE and CIN in forecasting. Each participant was asked to answer all the questions individually, except the open-ended questions, which could also be answered jointly for a small group of participants if they wished so. There were 23 such groups or individuals.

The first question asked how often CAPE/CIN were used by the forecasters when forecasting convective storms (Figure 8). 84% used CAPE either every time, or often, compared to 55% for CIN. Only a small fraction of respondents used it rarely or never, 8% and 24% for CAPE and CIN, respectively.

The participants were asked to indicate for what purpose they used CAPE and CIN (Figure 9). 83% mentioned the probability of storms, 60% the severity of storms, and a few mentioned the probability of hail and estimating the cloud top height (12% and 12%, respectively). Cloud top height can, by the way, not be directly inferred from either of these parameters.

Subsequently, participants were asked whether they were aware that CAPE and CIN can be calculated in different ways. Since filling in the questionnaire followed an introduction by the ESSL team on the various parcel source layers that can be selected for the calculation, it is assumed that participants interpreted this question as whether they had previously been aware of this. Indeed, 74% replied that

they had been aware of this, while 63% of all participants claimed that they were aware how CAPE and CIN were calculated from the NWP model data they work with in their forecast office (Figure 10).

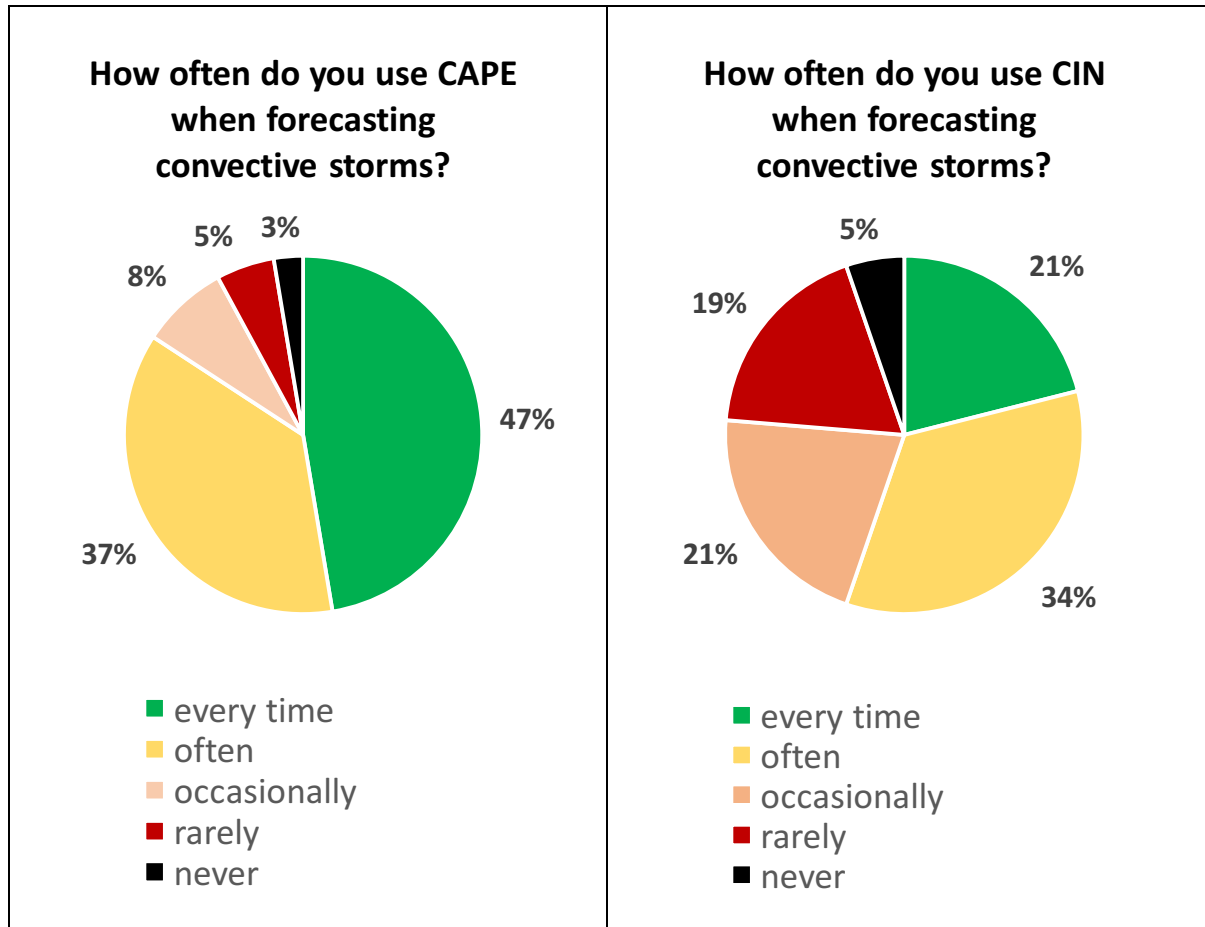


Figure 8. Responses by forecasters attending the ESSL Testbed on their frequency of use of CAPE and CIN (N=38).

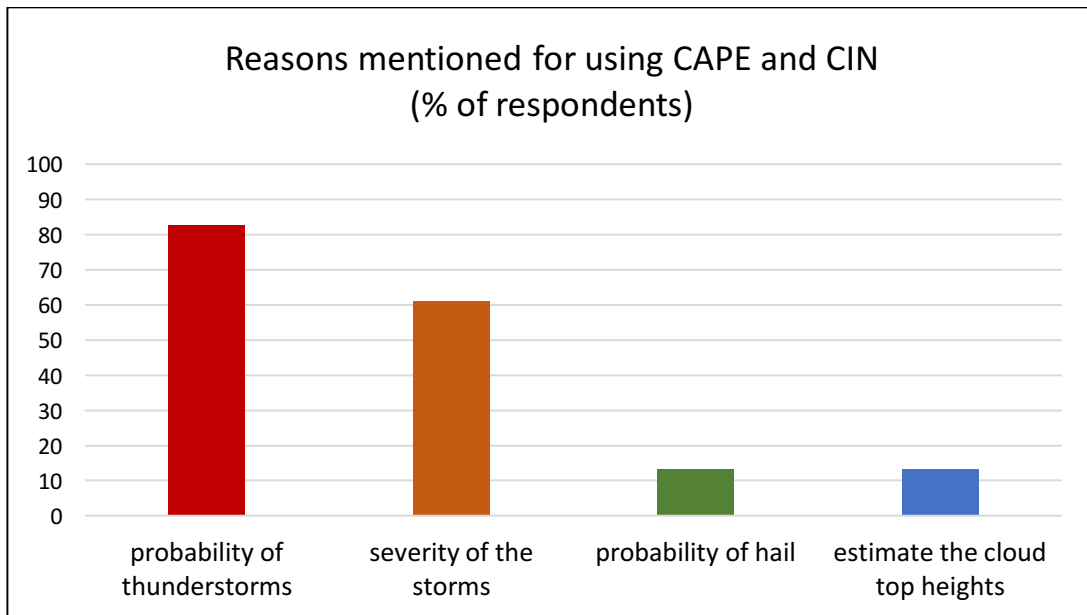


Figure 9. Reasons forecasters mention for using CAPE and CIN when forecasting (N=23).

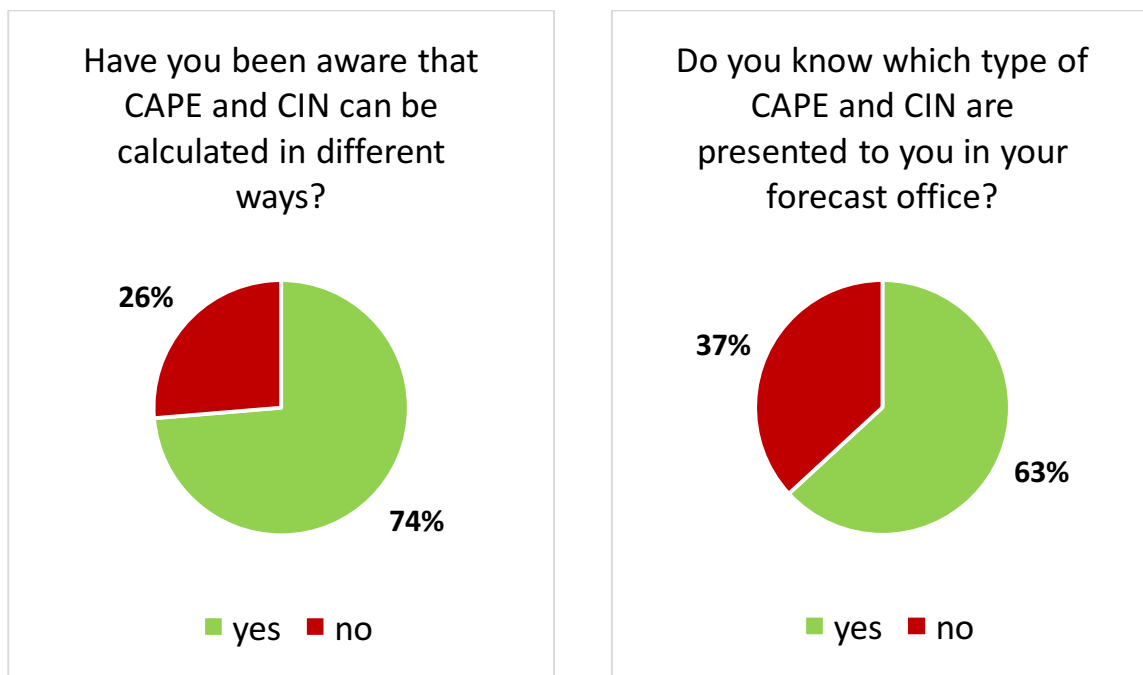


Figure 10. Questions about the use of CAPE and CIN in the forecast office (N=38).

Finally, the participants indicated their preferences of which type of CAPE or CIN should be used (Figure 11). 20 out of 23 indicated that they wanted to use MUCAPE and as many participants selected a form of MLCAPE. Of those who specified MLCAPE further, three wanted both MLCAPE50 and MLCAPE100, one only MLCAPE100, and nine only MLCAPE50. Fewer people indicated a preference

for a form of CIN, probably because they would like to have CIN for the same parcel as for which CAPE is calculated.

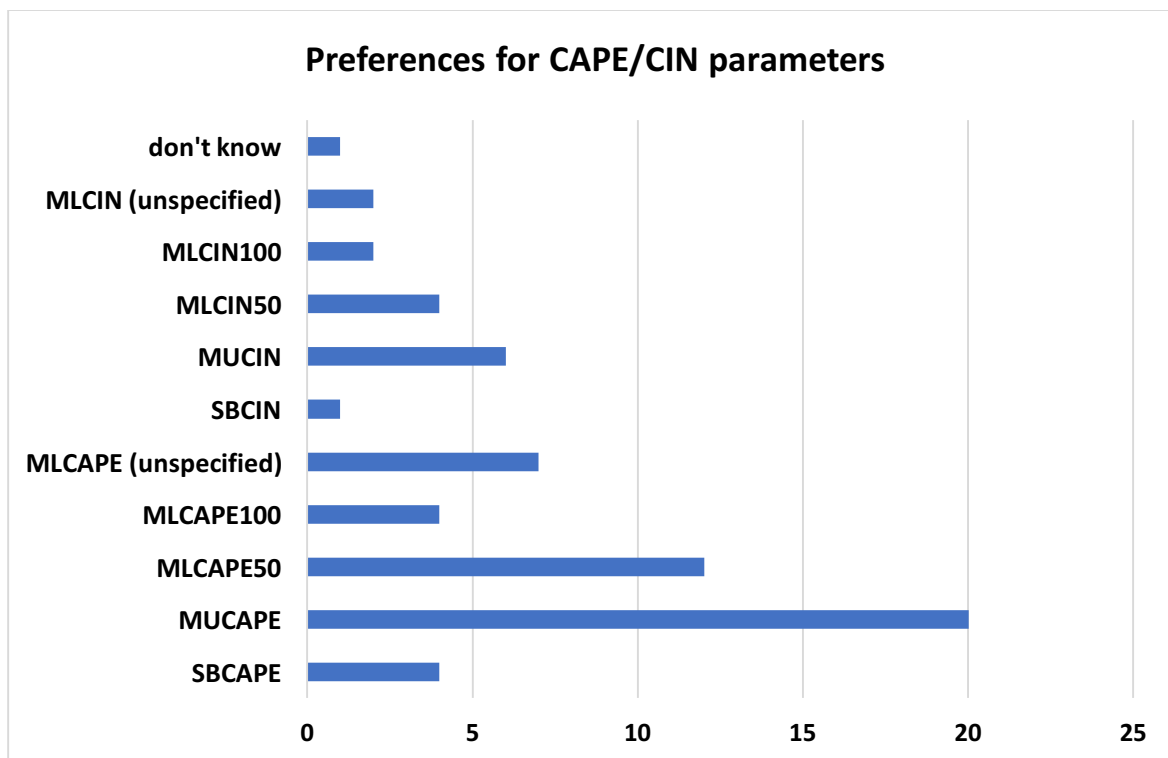


Figure 11. Mentioned preferences by forecasters for specific CAPE/CIN varieties with multiple answers possible ( $N=23$ ).

## 4 The computation of CAPE and CIN in numerical weather prediction models

### 4.1 CAPE and CIN from the IFS

In the Integrated Forecasting System (IFS) for diagnostic purposes CAPE is provided as a model output. It is currently computed from the parcel theory assuming a pseudo-adiabatic ascent (all condensate is removed as soon as it forms). For computational efficiency CAPE is approximated to:

$$CAPE \approx \int_{z_{dep}}^{z_{top}} g \left( \frac{\theta_{ep} - \bar{\theta}_{esat}}{\bar{\theta}_{esat}} \right) dz$$

using environmental saturated equivalent potential temperature  $\bar{\theta}_{esat}$  and equivalent potential temperature of the parcel  $\theta_{ep}$ :

$$\theta_{ep} = T_k \left( \frac{p_0}{p_k} \right)^{R/c_p} \exp \left( \frac{Lq_k}{c_p T_k} \right),$$

where  $T_k$ ,  $p_k$  and  $q_k$  are the temperature, pressure and specific humidity respectively of the parcel lifted from a model level  $k$ ,  $p_0 = 1000 \text{ hPa}$  is the reference pressure,  $c_p$  is the specific heat capacity of dry air at constant pressure,  $R$  is the gas constant of dry air and  $L$  is the latent heat of vaporization.  $\theta_{ep}$  is conserved during a pseudo-adiabatic ascent. CAPE is computed for parcels departing from each model level up to 350 hPa pressure surface. For parcels ascending from the lowest 60 hPa, mixed-layer values are used for 30 hPa deep layers. Hence, a surface parcel (parcel departing from the lowest model level) is not considered. The maximum CAPE from all the parcels is retained. Entrainment and detrainment are not considered in the CAPE computation (see Table 1).

CIN computation has been fully revised in the upcoming IFS cycle 47r1. In the revised version CIN is computed according to:

$$CIN = - \int_{z_{dep}}^{LFC} g \left( \frac{\theta_{vp} - \bar{\theta}_v}{\bar{\theta}_v} \right) dz$$

where  $\theta_{vp}$  and  $\bar{\theta}_v$  are the virtual potential temperatures of the parcel and the environment respectively. The level of free convection (LFC) is approximated with the level where CAPE exceeds a threshold of  $100 \text{ J.kg}^{-1}$ . CIN is computed for the same most unstable parcel for which CAPE is provided and apparently virtual temperature correction is accounted for.

## 4.2 Implementation of CAPE/CIN computation in other NWP models in ECMWF member states

An inventory of the ways the computations of CAPE and CIN have been implemented in NWP models operated by ECMWF member states has been made. To do so, contact persons at these services were contacted to answer a number of questions, or to provide the code in which the CAPE and/or CIN computations are carried out. ESSL was able to collect such information for the following models: AROME, ARPEGE, Unified Model (UM), ICON, COSMO and HiRLAM.

In all models, some form of CAPE is calculated, however in the Unified Model, this is done only for purposes within the model (the convective parameterization) rather than to provide data fields to be used by forecasters. The UK Met. Office states that of the two methods currently implemented, *neither can be interpreted as a generic measure of the conditional instability of the parcel.*

Table 1 summarizes the information obtained from the various centres and model code. The computations in these models differ in four ways:

1. the choice of the parcel that is lifted,
2. whether entrainment of environmental air is included,
3. the type of thermodynamic process assumed, and
4. whether the latent heat of freezing and disposition is considered.

### 4.2.1 The choice of the parcel

In the ARPEGE and AROME models, the computation is carried out for the most unstable parcel located between the surface and the level where the pressure equals 0.7 times the surface pressure. A similar choice is available in the ICON and COSMO models, where two types of parcels are taken: first, the most unstable parcel in the lowest 300 hPa of the atmosphere – which should deliver very

comparable results – and, second, a mixed-layer parcel that has the properties of the lowest 50 hPa. Like ICON and COSMO, the HiRLAM code also allows a 50 hPa mixed-layer parcel to be taken, or, alternatively, a 100 hPa mixed-layer parcel. HiRLAM also allows the computation of CAPE for the parcel having the highest wet bulb potential temperature ( $\theta_w$ ) in the profile<sup>2</sup>. In the UM, both boundary layer convection and mid-level convection is accounted for by selecting a parcel initiating from the lower part of the boundary layer, or any mid-level parcel that exhibits enough buoyancy.

#### 4.2.2 *Entrainment of environmental air*

In some NWP models, entrainment of environmental air into the ascending parcel is assumed, whereas in others it is not. Entrainment has the effect of lowering the parcel's buoyancy by mixing in neutrally buoyant air and inducing cooling by evaporation of hydrometeors in the entrained unsaturated air. It is clear that this is a process that occurs in real updrafts, however the rate at which this happens depends on many factors including the width of the updraft, the convective mode, and the amount of vertical wind shear: information that is not available in a vertical temperature and humidity profile.

The ARPEGE and AROME parcels assume a constant entrainment rate of  $10^{-4} \text{ m}^{-1}$ , and in HiRLAM it is likewise set to a particular constant value. In the UM, the *diagnostic parcel* that diagnoses whether convection is to be triggered does not, whilst the *main ascent* parcel does assume entrainment at a rate dependent on whether the convection is shallow, mid-level or deep. The parcels used to calculate CAPE and CIN in the COSMO and ICON models do not assume any entrainment.

#### 4.2.3 *Type of ascent; latent heat of freezing and disposition*

Various assumptions can be made with regard to the thermodynamic process that occurs when moist air, possibly containing a fraction of liquid and/or solid water, is lifted. One may, for instance, assume an adiabatic process in which no heat or mass is exchanged with the environment, rendering the entropy of the parcel and equivalent potential energy ( $\theta_e$ ) constant. This is called a reversible (or adiabatic) process, since bringing a parcel back to its original pressure after it has been lifted will bring it back to its original state. In contrast, one can assume that all liquid and solid condensate leaves the parcel the moment it is formed. In this assumption, all latent heat that is released is used to warm only the air-water vapour mixture, not the condensed water, which renders a lifted parcel a few °C warmer at the top of the troposphere, as shown by Emanuel (1994). During such pseudo-adiabatic ascent, the pseudo-equivalent potential temperature ( $\theta_{ep}$ ) is constant. In the models ICON, COSMO, HiRLAM and the diagnosis ascent of UM a reversible process (with or without entrainment) is assumed, whereas ARPEGE and AROME's parcels undergo pseudo-adiabatic ascent.

Another choice that must be made is whether the water vapour in the parcel only condenses to liquid phase or deposition and freezing of water are taken into account. The latter options are difficult as there is no fixed temperature at which deposition and freezing take place. Although these processes are ruled out above 0°C, clouds may contain water droplets at temperatures down to -37.5°C, in particular in strong updrafts of convective clouds (Rosenfeld and Woodley 2000).

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<sup>2</sup> This does not always equal the most unstable parcel (i.e. that with the highest CAPE).

	type(s) of parcel	entrainment of environmental air	type of ascent	latent heat of freezing considered?
IFS	Most unstable parcel of any model levels up to 350 hPa pressure level; surface (lowest model level) parcel not considered, instead mixed layer 30-hPa parameters used in the lowest 60 hPa	no	pseudo-adiabatic ( $\theta_{ep}$ constant)	no
ARPEGE, AROME	most unstable parcel of any parcel up to 0.7 of surface pressure	yes, entrainment of 10-4 m-1	in principle pseudo-adiabatic ( $\theta_{ep}$ constant), but with entrainment	yes, below 0°C
UM <sup>3</sup> 1. diagnosis 2. main ascent	1. from 0.1 times height of the boundary layer, or where $T_v$ <sup>4</sup> stops decreasing with height when going up from surface. 2. lifted either from the LCL determined from 1, or from any level above the boundary layer. In both cases, a small temperature excess is added to render the initial parcel buoyant	1. no 2. yes, different rates for shallow, mid-level, and deep convection	1. reversible, i.e. condensate stays in parcel ( $\theta_e$ constant) by performing a dry ascent first and then adding the right amount of latent heating by an iterative process 2. pseudo-adiabatic ( $\theta_{ep}$ constant)	1. yes, below 0°C, ice is formed 2. yes, all remaining liquid condensate freezes at $T = -10^\circ\text{C}$
ICON, COSMO	1. most unstable parcel in the lowest 300 hPa 2. mixed-layer parcel (with mean properties of the lowest 50 hPa of the profile)	no	reversible ( $\theta_e$ constant)	no
HIRLAM	1. parcel from the level with maximum wet bulb potential temperature ( $\theta_w$ ) <sup>5</sup> 2. 50 hPa mixed-layer parcel 3. 100 hPa mixed-layer parcel	yes, a constant entrainment is assumed	reversible, ( $\theta_e$ constant)	yes, below a fixed temperature
ESSL code provided to ECMWF	1. lowest model level 2. all model levels up to 50 hPa above the surface pressure 3. all model levels up to 100 hPa above the surface pressure 4. the parcel that gives the highest cape	no	pseudo-adiabatic ( $\theta_{ep}$ constant)	no

Table 1. Comparison between CAPE/CIN calculations in the IFS and various models operated by ECMWF member states.

<sup>3</sup> There are two routines that calculate CAPE and CIN in the UM. Neither of them is intended for use as a diagnostic output for forecasters, but instead have uses within the model. They can be used to investigate the behaviour of the convective scheme.

<sup>4</sup> Actually instead of  $T_v$ , an approximation of  $T_v$  is used.

<sup>5</sup> This procedure will not always yield the desired result, since  $\theta_w$  may be maximized above the convecting layer.



In the parcels in the ARPEGE and AROME models, and the *diagnostic* UM parcel, all condensate freezes at 0°C, in the HiRLAM parcel below a fixed temperature (that was not specified in the code), which is set to -10°C in the UM *main ascent* parcel. In ICON and COSMO no freezing is included in the parcel curve.

To compute parcel buoyancy, which is integrated vertically to yield CAPE and CIN, it makes a difference whether the liquid and solid condensate is considered to be part of the parcel, and whether the lower density due to the contained water vapour is considered. The importance of the former effect increases along the parcel's upward path, whereas the latter effect is most important at lower altitudes. In all reviewed NWP models, all condensate is excluded from the buoyancy calculation, and in all models, too, the so-called virtual temperature correction (Doswell and Rasmussen 1994) is made which accounts for lower density of the water vapour in the air parcel.

### 4.3 Implementation of CAPE and CIN calculations by ESSL and recommendations

ESSL has provided ECMWF with a code to calculate CAPE and CIN for which it has made a number of choices about the calculation, similar to those that the developers of the NWP models listed above have made.

#### 4.3.1 *The choice of the parcel*

The code is capable of calculating surface-based CAPE and CIN, which use the lowest model level as the fixed starting point of the parcel, as well as two (50 and 100 hPa) mixed-layer CAPE and CIN options, and an option for the most-unstable parcel. The feedback from the forecasters at the ESSL Testbed 2019 indicates that a form of MLCAPE and MUCAPE are both thought to be important, in contrast to SBCAPE. It was often noted that MLCAPE was thought to be more representative of the CAPE of air flowing into a storm than SBCAPE, and that the latter would therefore not be very useful. Among those who specified the depth of the mixed-layer, a preference for MLCAPE50 existed, possibly because some weather services in Europe have already made that choice. Indeed, the consideration that the boundary layer contributing the potentially buoyant air to a storm's updraft is sometimes shallower than 100 hPa may have motivated this choice.

To assess the possibility of elevated convection, MUCAPE would be needed in addition to MLCAPE50. To be consistent, one may argue that a mixed-layer parcel should also be used for most-unstable CAPE. However, elevated layers do not usually feature superadiabatic lapse rates or moist layers such as those that happen in the lowest metres of the atmosphere over strongly heated land or sea masses. Therefore, vertical mixing of elevated parcel source layers seems not to be very important.

Few forecasters explicitly addressed CIN in their reviews, but it is implied that CIN should be calculated for the same parcels.

#### **Recommendation:**

*ESSL recommends providing forecasters both with a mixed-layer CAPE (preferably a 50 hPa mixed-layer parcel) and most unstable CAPE, and CIN calculated for the same parcels.*

#### 4.3.2 *Entrainment of environmental air*

Some NWP models assume entrainment of environmental air in the parcel curves. While entrainment has a role within the convective parameterization of a model, ESSL does not recommend its inclusion in the CAPE computation, because the true rate of entrainment is poorly known and depends on many factors - discussed above - that are not reflected in a modelled or observed sounding. Any assumed rate of entrainment may produce an under- or overestimation of the true buoyancy of air in a storm's updraft, but it is not known which it is.

In contrast, assuming a zero entrainment rate will always yield an overestimate of parcel buoyancy, but to an unknown extent. Forecasters usually consider CAPE to assess the potential of storms (the joint presence of the ingredients - steep lapse rates and low-level moisture) being aware that other (missing) ingredients may still impede the initiation of a storm. As such, it is probably easier to use a parameter that tends to overestimate the potential of storms, rather than one that sometimes overestimates the potential while, on other occasions, it does not indicate a potential for storms that does, in fact, exist.

#### **Recommendation:**

*ESSL recommends assuming that no entrainment of environmental air into the rising parcel will occur when calculating CAPE and CIN.*

#### 4.3.3 *Type of ascent; latent heat of freezing and disposition*

As written above, assuming reversible or irreversible (pseudo-adiabatic) ascent leads to different amounts of parcel buoyancy and hence CAPE and CIN (Manzato and Morgan 2003; Williams and Renno 1993). The pseudo-adiabatic ascent gives the highest buoyancy, as the released latent heat is not used to heat the condensate, because it is assumed to leave the parcel immediately.

In reality, some condensate will likely leave a rising air parcel and some will remain in it, and the released heat would be in between these two extremes. This, again, cannot be estimated *a priori* from a sounding. Pseudo-adiabatic ascent will be an upper bound to the true buoyancy of rising parcel, and likely be an overestimate in the lower troposphere.

Pseudo-adiabatic ascent is also easier and computationally cheaper to compute than reversible ascent, as there is no need to track the contained amounts of liquid water and ice in the parcel that have a heat capacity and may freeze, releasing latent heat of freezing.

Specifically, Früh and Wirth (2007) have compared the buoyancy of ascending parcels in a tropical standard atmosphere under various assumptions including 1) reversible ascent with freezing of the liquid water and 2) pseudo-adiabatic ascent. Their results show that pseudo-adiabatic ascent leads to higher buoyancy before reaching the level where condensate freezes, similar buoyancy after the condensate freezes, and somewhat lower buoyancy in the upper troposphere.

In the mid-troposphere, after freezing, the additional weight of any water assumed to remain in the parcel apparently has a similar but opposite effect on parcel buoyancy as the latent heat of freezing of that water. Because of this - and likely because of reasons of simplicity, not having to assume a temperature at which freezing occurs, a lower computational cost - some modellers have chosen to assume pseudo-adiabatic ascent (AROME, ARPEGE) for their CAPE and CIN calculations (Table 1).

In addition, for American-developed models such as WRF and GFS, pseudo-adiabatic ascent is also assumed.

In HiRLAM, however, reversible ascent is assumed with freezing at a constant temperature. Früh and Wirth (2007) note that assuming the instantaneous freezing of liquid water introduces a sudden spike in buoyancy on the parcel's vertical profile and therefore instead recommend a gradual freezing between  $-5^{\circ}\text{C}$  and  $-35^{\circ}\text{C}$  as a pragmatic approach.

We note here that it is customary to assume pseudo-adiabatic ascent in NWP, but that this may lead to an overestimation of parcel buoyancy in the lower troposphere. Especially when CIN is small, because the parcel is close to neutral buoyancy, the difference in CIN between pseudo-adiabatic and reversible ascent can be high. A warm cap or lid preventing convective initiation may not seem to be present in a profile based on pseudo-adiabatic process, whereas it is present in reality.

A reversible ascent during which condensate freezing within some range of temperatures is assumed, as proposed by Früh and Wirth (2007) – their choice being between  $-5^{\circ}\text{C}$  and  $-35^{\circ}\text{C}$  — is likely a more accurate approximation. A further study into the significance to forecasters of these differences in typical mid-latitude convective situations could be of interest.

### **Recommendation:**

*ESSL recommends assuming pseudo-adiabatic ascent for parcel calculations used to diagnose CAPE and CIN, however noting that pseudo-adiabatic ascent may underestimate (overestimate) CIN (CAPE) compared to reversible ascent.*

#### *4.3.4 Some practical considerations*

Parcel computations are expensive because vertical integrations need to be done to obtain the buoyancy of the lifted parcel, at least during its phase of saturated ascent. In the code developed by ESSL and tested on ECMWF IFS data, we reduce the cost by pre-calculating the temperature profile of a large numbers of parcels with differing initial pseudo-equivalent potential temperatures  $\theta_{ep}$  and storing these data into a lookup-table. The table is a matrix of parcel temperatures  $T_{\text{parcel}}$  as a function of the parcel's  $\theta_{ep}$ , which is conserved during ascent, and its pressure  $p$ , i.e.  $T_{\text{parcel}}(\theta_{ep}, p)$ . With this lookup-table available, evaluating the temperature of any lifted parcel reduces to interpolating the value of  $T_{\text{parcel}}$  from nearby values in the lookup table. This leads to a considerable reduction of computation time.

Another issue concerns the selection of the parcel with highest CAPE, i.e. the “most unstable” parcel, which can be done by calculating CAPE for parcels originating from all available vertical levels and then selecting that with the highest CAPE. However, this is inefficient because of the large computational expenses involved in the repeated vertical integrations. To mitigate this problem, one can make a pre-selection of parcels that can be the most unstable. Often, this will be the parcel with the highest  $\theta_{ep}$ . However, situations are thinkable in which the highest  $\theta_{ep}$  is found well above a convecting layer and does not exhibit the maximum CAPE in the profile. This may, for example, occur when a warm front with high humidity and temperature in the upper troposphere approaches. That being said, the most-unstable parcel will always originate from a level which is a local maximum of  $\theta_{ep}$ . A pre-selection of all parcels that meet this criterion can be made in order to reduce the number of parcels for which CAPE needs to be evaluated in order to identify the parcel with the highest CAPE. This approach also leads to a considerable reduction of the computation time.

## 5 Future ECMWF plans

Based on the ESSL study presented here, ECMWF is revising the CAPE and CIN provided as a model output from the IFS.

First, ECMWF plans to make available the following new CAPE and CIN parameters according to the parcel that will be considered during the vertical ascent:

- mixed-layer CAPE (MLCAPE) and mixed-layer CIN (MLCIN) referring to CAPE and CIN of a parcel representing the mean conditions of the lowest atmospheric layer. Both options for the depth of this layer, 50 and 100 hPa discussed in this review, will be considered during the test period and a decision will be made at a later stage whether to keep them both or select one of them;
- most unstable CAPE (MUCAPE) and most unstable CIN (MUCIN) referring to CAPE and CIN of the most unstable parcel (the parcel with the highest CAPE); the departure level of the most unstable parcel in Pascals (Pa) will also be provided as an IFS model output.

All new CAPE and CIN parameters will take into account the virtual temperature correction (Doswell and Rasmussen 1994) via virtual potential temperature  $\Theta_v$  which will replace the equivalent potential temperature  $\Theta_e$  in the computation. The parcel ascent will continue to be considered pseudo-adiabatic.

For the time being, the CAPE described in Section 4.1 will continue to be provided and used for the EFI and CAPE-shear computations.

These new CAPE and CIN parameters will be made available in near future after the migration of ECMWF's data centre to Bologna, Italy.

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