Clear-Air Turbulence Parameterisation for Long-Range Applications of a Lagrangian Particle Model

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Introduction

Transport and dispersion models usually include parameterisations for turbulence in the atmospheric boundary layer (ABL). However, long-range transport often takes place above the ABL (**?**), and studies of transport processes in the free atmosphere, e.g., of stratospheric intrusions in the troposphere, are becoming more common (**?**). Presently, off-line transport models either ignore turbulence outside the ABL, or treat them in a very crude way. For example, the Lagrangian particle dispersion model (LPDM) Flexpart (**?**), which we are using, applies a “background” turbulence characterised by standard deviations $\sigma_{u,v,w}$ of the wind components proportional to the variance of the mean wind around the grid point and a fixed Lagrangian time scale T_l, plus a horizontal meandering with a fixed $\sigma_{u,v}$=0.3 ms^{-1} and a T_l of 3600 s. Recently, a parameterisation for subgrid-scale convective transports was added (**?**).

We have now developed a parameterisation for shear-induced turbulence. This type of turbulence is often subsumed under the term clear-air turbulence or CAT (in contrast to turbulence in convective clouds). However, CAT events can also be caused by breaking of gravity waves. Thus, we use the abbreviation sCAT for shear-induced CAT.

The scheme is described on this poster. It consists of two steps:

1. Determination of turbulent regions
2. Quantification of turbulence (σ_w and T_{lw})

We present examples and a 1-month climatology of sCAT as diagnosed by this scheme.

Determination of turbulent regions

The determination of the turbulent regions is based on a modified version of the CAT index TI2 after **?**). It emerged as one of the best indicators in a comparative study of CAT indicators based on aircraft turbulence data and pilot reports (**?**).

The original TI2 index is defined as

$$\text{TI2} = |\text{VWS}| \times (\text{DEF} + \text{CVG})$$

where VWS is the vertical shear of the horizontal wind (VWS), DEF is deformation and CVG convergence. It is a parameterisation of the kinematic frontogenetic intensity $\partial|\nabla\theta|/\partial t$ where θ is potential temperature.

Our modified sCAT index is calculated as:

$$\Theta = \frac{-1}{\sqrt{{\theta_x}^2 + {\theta_y}^2}} \left[(\theta_x)^2 u_x + \theta_x(\theta_y v_x + \theta_y u_y) + (\theta_y)^2 v_y\right]$$

where Θ is our modified turbulence index, u, v are the horizontal wind components, and subscripts are denoting partial derivatives which are taken on pressure levels.

It is contains less simplification than the original TI2, he main difference being that the real angle between the deformation axis and the potential temperature gradient is considered, instead of assuming maximum effectiveness of deformation. This should reduce the amount of “false alarm” cases.

A few smaller modifications were also made:

- Elimination of all isolated one-grid cell patches (corroborated by findings in the validation studies that CAT probability is smaller for small contiguous area diagnosed as CAT-prone).
- Consideration of static stability. The Richardson number contains both VWS and stability but is ignored in TI2. Therefore, sCAT is diagnosed frequently in the stratosphere, a region where the index was not validated and for which it is not meant. To avoid that, we excluded all regions where the static stability exceeds the value assumed for the thermal tropopause definition, –0.2 K / 100 m.

Quantification of turbulence

For the implemenation in a LPDM, turbulence needs to be quantified in terms of the standard deviation of the vertical wind, σ_w, and the related Lagrangian time scale, T_l. Explicit horizontal turbulence is not considered, as the combined effect of σ_w and VWS is expected to dominate the horizontal mixing.

We rely on one of the standard turbulence parameterisation schemes of the MM4 model, successfully applied for the simulation of turbulent decay of stratospheric intrusions in an idealised set-up (**?**). It calculates the vertical turbulent diffusion coefficient K for regions where the numerically approximated, grid-scale Richardson number Ri exceeds its critical value Ri_c as

$$K = Al^2 \left|\frac{\partial\vec{V}}{\partial z}\right| \frac{Ri_c - Ri}{Ri_c}$$

where A is a dimensionless constant of the order of 1, and l is a length scale, assigned a constant value of 40 m by **?**). It would be desirable to make l dependent on the static stability, but we have not yet found a suitable approach.

As numerous aviation meteorology studies have shown that Ri derived from NWP products is not a good CAT predictor in practice, we replace this term by the inverse of our turbulence index Θ. With $\sigma_w = K/l$ and scaling arguments for T_l we get:

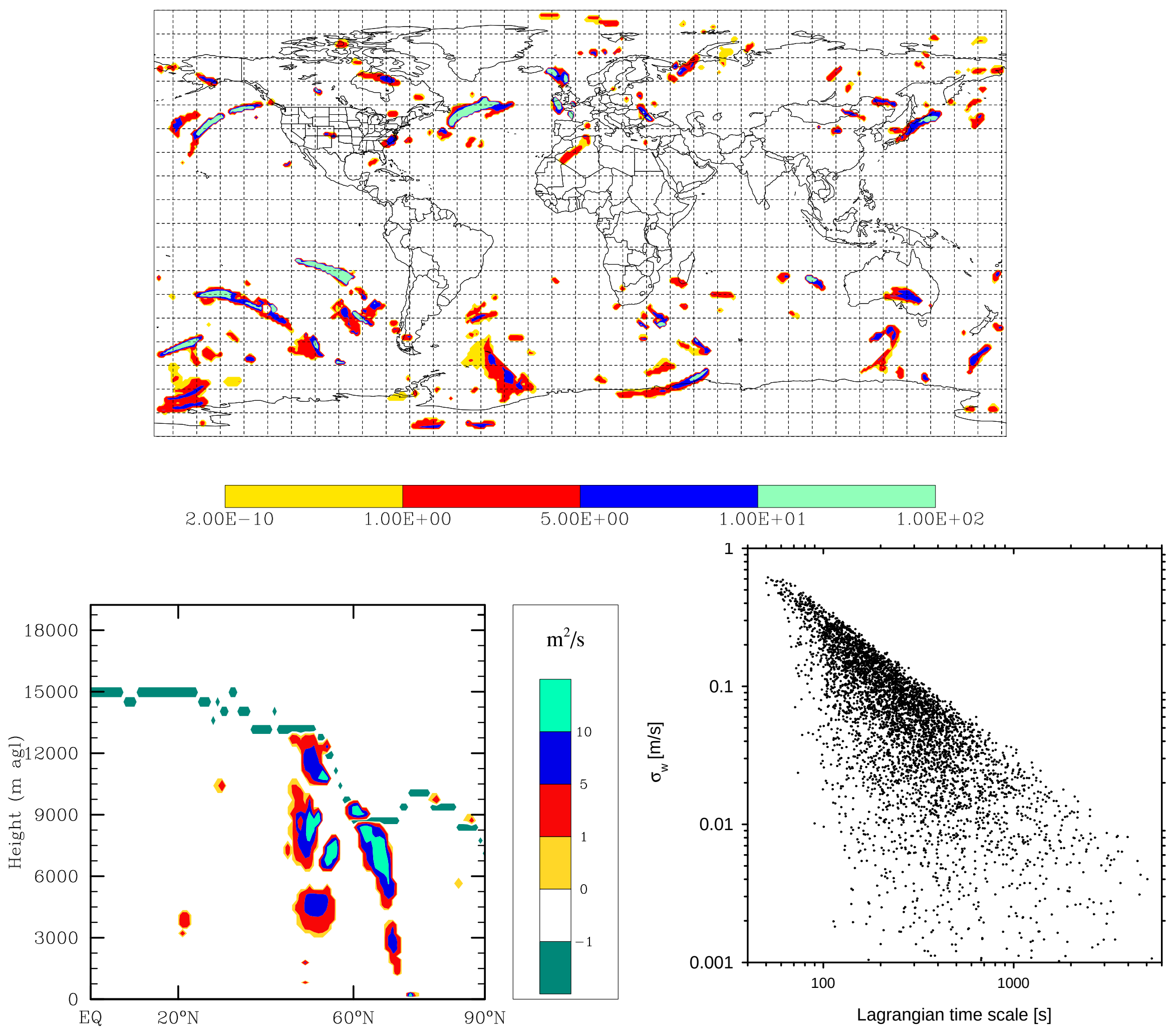
$$\sigma_w = Al \left|\frac{\partial\vec{V}}{\partial z}\right| \left(1 - \frac{\Theta^{-1}}{\Theta_c^{-1}}\right); \quad T_l = B \left|\frac{\partial\vec{V}}{\partial z}\right|^{-1}$$

where B isanother constant of the order of 1. Lacking better information, for the moment we assume $A = B = 1$.

Note that the length scale has only linear impact on σ_w, as compared to quadratic for K.

Results - Single case

Application to ECMWF fields, 1° 60 levels
Example of the K field (2000-10-01/00UTC).



Horizontal field of K in m^2 s-1 at 8700 m agl

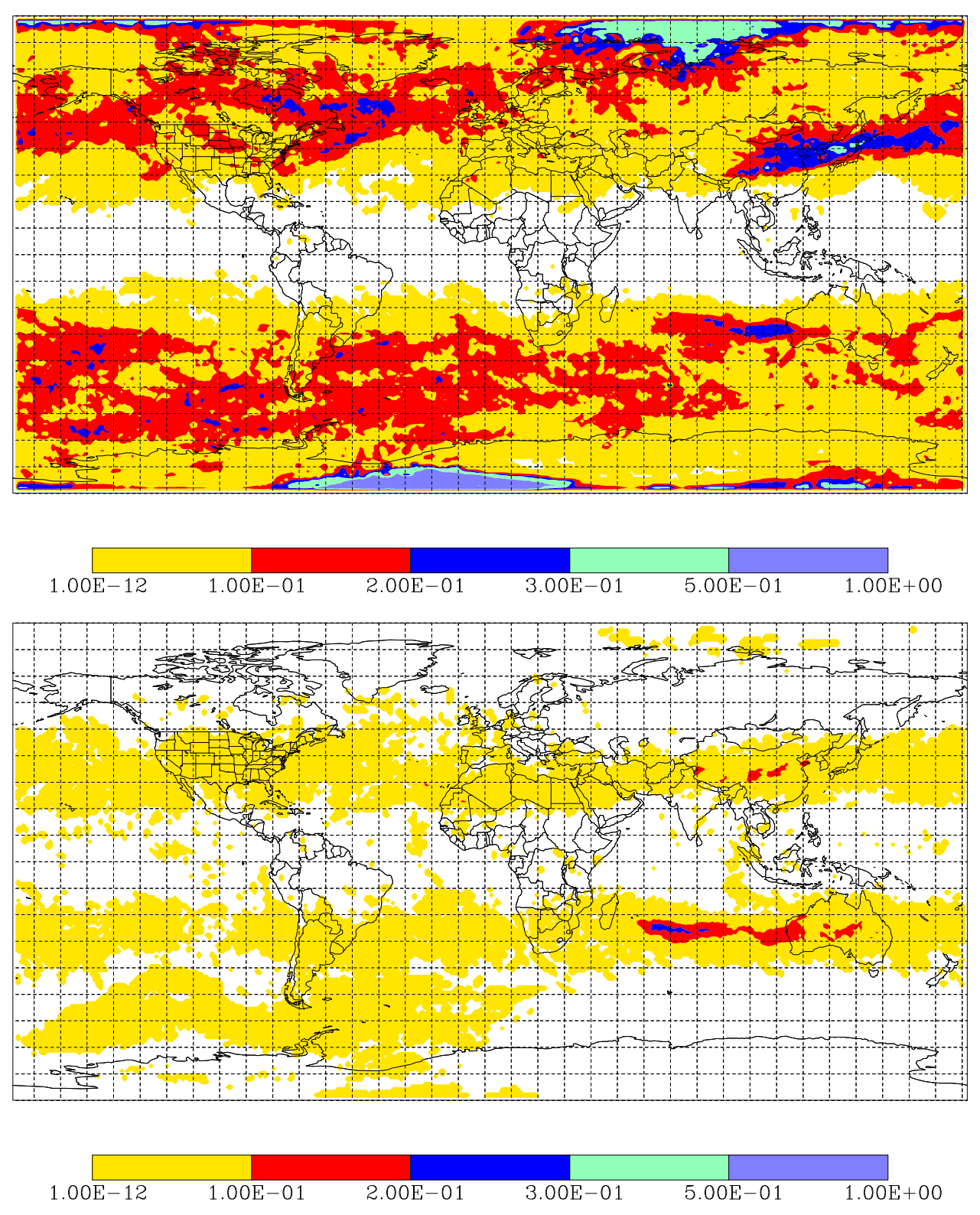
Top: horizontal field,
bottom left: Cross-section at 10°W (tropopause marked dark green).
Bottom right: Scatter plot of vertical turbulent velocity versus Lagrangian time scale (2000-10-01/00UTC, all levels).

Values of K typically range between 0.1 and 20 m^{2}s^{-1}. As we have used a constant l here, σ_w and K values are directly related: $K = \sigma_w \cdot 40$ m.

At the 9 km level, sCAT is mostly found in high and mid-latitudes, tied to synoptic systems (jet streams). Some turbulence is also found close to the ABL top. This could be due to low-level jets. The fact that high turbulence is related to high vertical wind shear (which is the inverse of T_l) is clearly visible in the scatter plot.

Results - Global Climatology

The mean frequency of sCAT at 8 km asl and at 15 km asl during October 2000.



We see that at the 8 km level sCAT is concentrated along the mid-latitude jet positions and over some polar areas (the reason for the latter phenomenon is not clear). It is absent in the tropical region.

At 15 km, sCAT is much less frequent and seems to be related to the subtropical jet.

References

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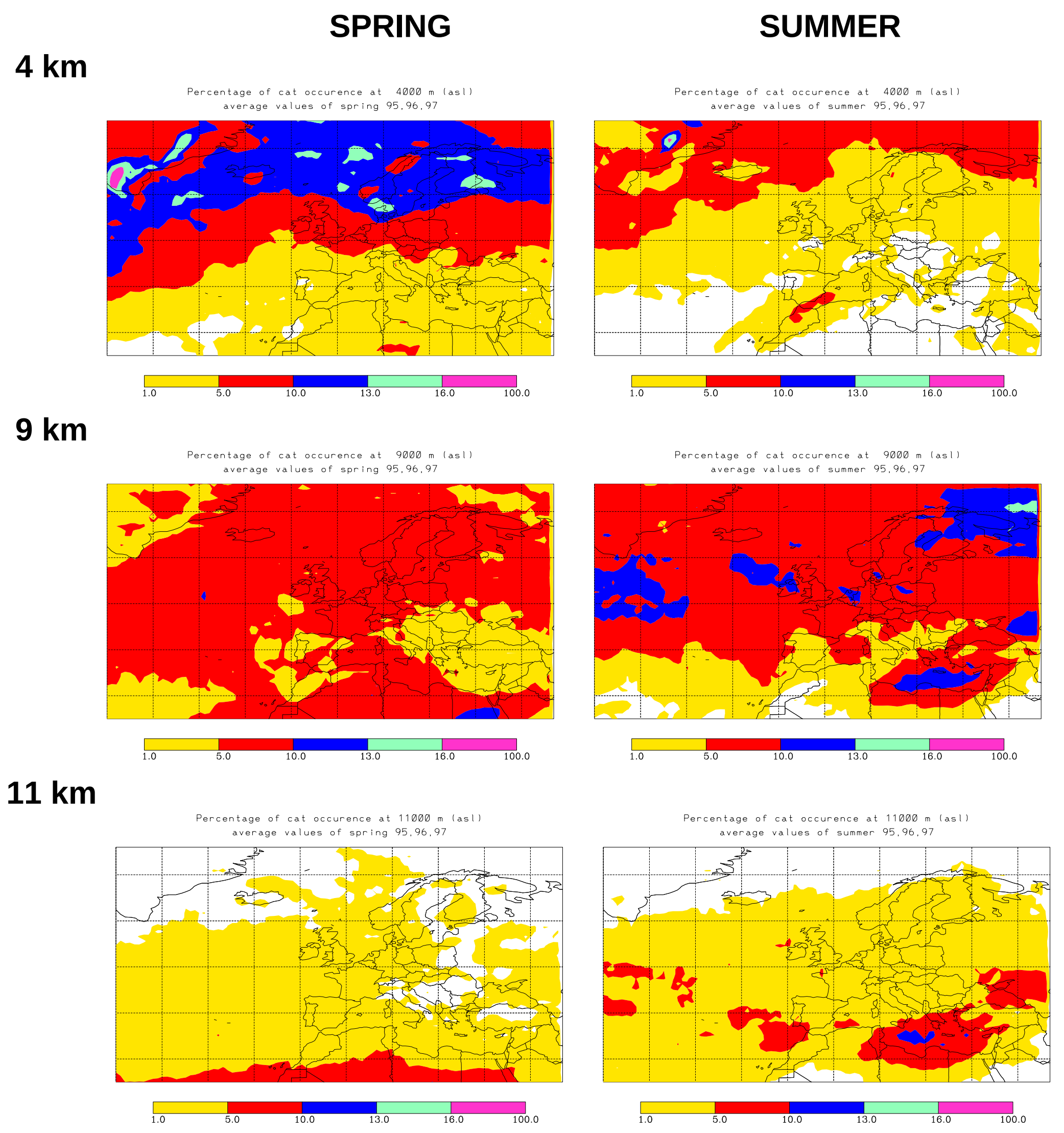
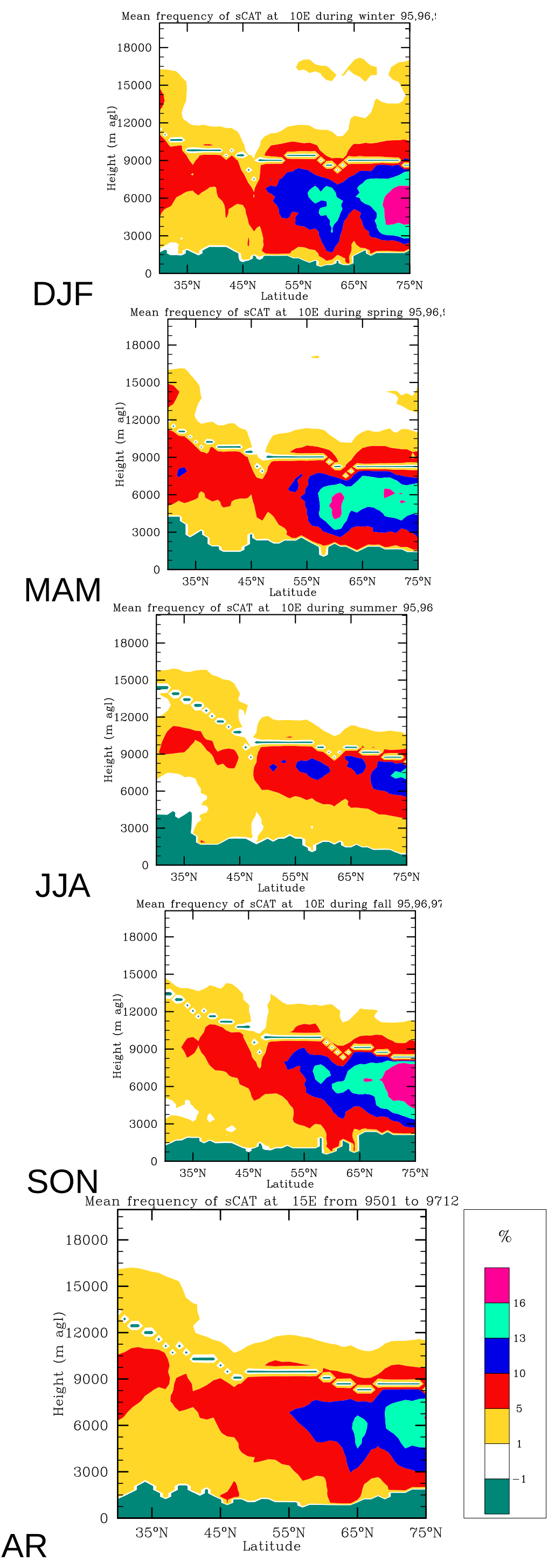
Results - Regional Climatology

These results are based on 1°, 31 level ECMWF data of the years 1995-1997. They show the percentage of sCAT occurrence in spring and summer at three different levels.



At lower levels, there is a strong annual (minimum in summer) and latitudinal (maximum in the high latitudes) variation. At the jet level (9 km), the annual variation is weaker and we can see both the influences of the subtropical and the polar jet. At the level of 11 km, sCAT is less frequent and mainly due to the subtropical jet; we can see that its position is shifted northwards in summer.



Zonal cross-section of the sCAT probability at 10°E in the four seasons and the whole year.

Average position of the tropopause and the ABL is indicated by dark green colour. The area is the same as for the horizontal sections shown above.

We can see that in winter sCAT is frequent in a much larger portion of the atmosphere than in summer, and that sCAT is most frquent below the tropopause, as expected. A surprising feature yet to be explained is the maximum in winter and fall at the pole, visible also in the other plots shown.

Conclusions and outlook

A scheme has been developed to diagnose regions of shear-induced turbulence in the free atmosphere from NWP model output, and to derive the necessary quantities for implementation in a LPDM. A basis for better determination of the constants (A, B, Θ_c) and a stability-dependent formulation for l would, however, be desirable. The next steps will be to collect practical experience with the scheme. However, validation is hampered by the fact that most long-range tracer experiments include only few useful measurements in the free atmosphere, if at all.

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