



# **Application of transilient turbulence theory to a mesoscale dispersion model**

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## **Abstract**

The University of Aveiro is concerned with the implementation of an advanced scheme for the simulation of turbulence within the non-hydrostatic mesoscale model MEMO. The main goal of this paper is to investigate the effect of vertical non-local turbulent mixing in the formation and development of mesoscale processes using the transilient turbulent theory (TTT). The MEMO version which includes TTT was applied to the Aveiro region: Results of this application were compared with results of a meteorological campaign. Simulations included the dispersion of a passive pollutant released by a paper-mill plant.

## **1 Introduction**

The original version of the non-hydrostatic prognostic mesoscale model MEMO was developed at the University of Karlsruhe, in Germany. A detailed description of the model MEMO is given by Flassak [1] and Moussiopoulos et al [2]. In the last years MEMO has been installed and used at several research institutions throughout Europe. The model has been successfully applied and verified for various European airsheds including Athens, Barcelona, Lisbon, Zurich and Thessaloniki. Further development of MEMO is currently undertaken at several European universities.

It is well known that even for simple cases, the complex structure of turbulent motions over many scales produces transport of momentum, heat, moisture and pollutants which are not adequately described using simple diffusion theories. The primary goal of this paper is to investigate the effect of vertical non-local turbulent mixing in the formation and development of



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mesoscale processes using the transilient turbulent theory, as developed by Stull [3] and Driedronks [4].

### 2 The Transilient Turbulence Theory

The transilient turbulence theory (TTT) parameterizes the turbulent fluxes by using the values of the transported quantities at many points in space. TTT incorporates a more physical representation of the mixing process, by which the role of eddies of various sizes are accounted for separately, instead of restricting the mixing to adjacent levels.

According to TTT the amount of air that mixes from any source altitude to any destination altitude can be described by a matrix [C] of dimension (N x N), where N is the number of levels in the vertical grid. The element  $c_{ij}$  is called the transilient coefficient and represents the amount of air that arrives at level  $i$  from level  $j$  during one time step. Estimates of the transilient matrix can be calculated based on a parameterization of the turbulent kinetic energy equation.

#### 2.1 Implementation of TTT to MEMO

The implementation of TTT into MEMO [5] requires the calculation of the transilient matrix. The parameterization developed for this purpose must respond to the variations of the mean state caused by the body forcings and boundary conditions, as suggested by Raymond and Stull [6]. Following these authors, each model forecast timestep was split into five parts: i) the standard non-turbulent calculations; ii) computation of a transilient matrix for vertical mixing for each column; iii) vertical mixing based on the computed matrix; iv) computation of horizontal mixing potentials; and finally v) horizontal mixing.

#### 2.2 Parameterization of the transilient matrix

The parameterization presented by Stull and Driedronks [4] was used to compute the transilient coefficients. Considering a simplified form of the turbulent kinetic energy (TKE) equation, these authors hypothesise that this equation can be interpreted in a non-local sense. After a non-local normalisation of the TKE equation, it is possible to calculate the mixing potential  $Y_{ij}$  between two levels  $i$  and  $j$  (for  $i \neq j$ ):

$$Y_{ij} = \frac{T_0 \Delta t}{(\Delta z)_{ij}^2} [(\Delta U)_{ij}^2 + (\Delta V)_{ij}^2 - \left(\frac{g}{R_c \theta_{vi}}\right)(\Delta \theta_v)_{ij} |\Delta z_{ij}|] - \frac{D \Delta t}{T_0}$$

where  $(\Delta U)_{ij}$  and  $(\Delta V)_{ij}$  are the wind speed differences, and  $(\theta_v)_{ij}$  is the potential temperature difference between each pair of grid points. The distance

between the grid points is  $\Delta z_{ij}$ . The previous expression incorporates a timescale  $T_0$ , a critical Richardson number  $R_c$  and a dissipation parameter  $D$ . The off-diagonal transilient coefficients for  $n$  vertical levels are parameterized by:

$$c_{ij} = \frac{m_j Y_{ij}}{\max_i \left( \sum_{j=1}^n m_j Y_{ij} \right)}$$

where  $m_j$  is the mass of air within grid layer  $j$ . The elements on the main diagonal are given by:

$$c_{ii} = 1 - \sum_{\substack{j=1 \\ j \neq i}}^n c_{ij}$$

### 3 Application of MEMO to a coastal region

#### 3.1 The Aveiro region

The region under study is a coastal area of approximately 100 km x 70 km in the central part of Portugal (40.7°N). The topography is dominated by a large lagoon which extends around 35 km in the North-South direction (see Figure 1).

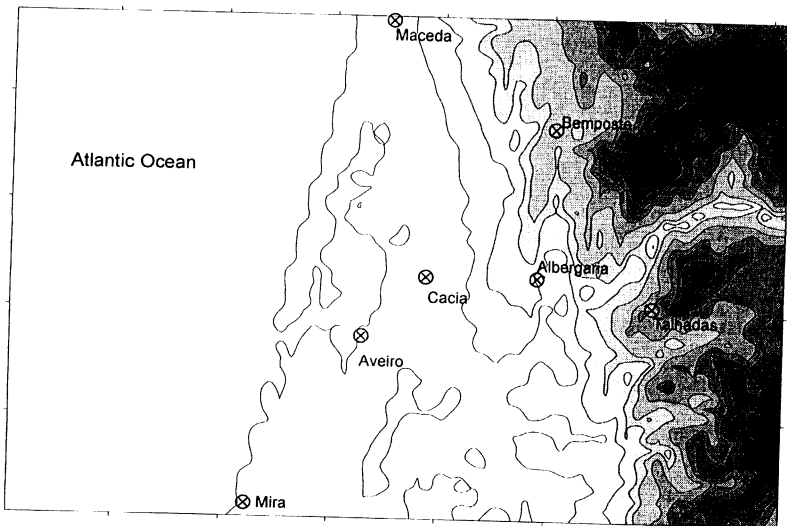


Figure 1 - The Aveiro region (1:600000). Topographical isolines for 0, 50, 100, 200, 400 and 800 m are represented.



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The western part of this region, surrounding the Aveiro lagoon, is relatively flat. The eastern part of the domain is characterised by rough terrain that follows 3 mountain ranges: Serra da Arada (reaching 1119 m above sea level), Talhadas (804 m) and Serra do Caramulo (1071 m). The topography is also affected by the river Vouga that cuts a deep valley between the Serra de Arada and Talhadas.

A meteorological campaign was conducted between August 24<sup>th</sup> and September 10<sup>th</sup> 1992 in the Aveiro region. A measurement network was in continuous operation during the period of the campaign.

Surface measurements were performed on 5 stations surrounding the Aveiro lagoon (Fig. 1):

- Cacia - Altitude 4m. Hourly measurements of wind (W), temperature (T) and humidity (H) at 10 and 30 m.
- Bemposta - Altitude 230 m. Hourly measurements of W at 12 m.
- Talhadas - Altitude 350 m. Half-hourly measurements of W, T and H on a 8.5 m mast.
- Maceda - Altitude 5m. Hourly climatological data.
- Mira - Altitude 5 m. Continuous wind measurement on a 10 m mast.

In addition to the surface network, vertical soundings of wind (radiosondes, pilot balloons and Doppler acoustic sounders) and temperature (radiosondes) were obtained in two locations, 10 km apart, perpendicular to the coast line (Fig. 1):

- Aveiro - Altitude 5 m. Doppler sodar, used for measuring the wind profiles in the first few hundred meters. 4 daily radiosoundings (W and T) were made. During typical sea-breeze days pilot balloons were released.
- Albergaria - Altitude 100 m. Doppler sodar measurements and pilot balloons.

### 3.2 MEMO Application

The MEMO model was applied to the region represented in Figure 1. The modelling domain is 72 km x 48 km x 6 km with a horizontal grid spacing of 2 km. In the vertical direction the grid consists of 20 layers non-equidistant with a minimum grid spacing of 20 m near the ground. Simulations included the dispersion of a passive pollutant released by a paper-mill plant located in Cacia. The atmospheric pollutant was released at 100 m above ground level.

MEMO was applied using two turbulence scheme: (i) the “standard” 1.5 order turbulence closure technique and (ii) the TTT. Results of the applications were compared with meteorological campaign data acquired during the 5th of September 1992.

### 3.3 Meteorological results

Figure 2 shows the comparison between the temporal evolution in Cacia of wind direction, wind speed and temperature measured during the campaign and results obtained with MEMO using the local and non-local turbulence scheme.

Meteorological data evolution in Cacia is marked by mesoscale effects, particularly, by the onset of the sea-breeze. During most of the night, measurements show a weak ( $< 1 \text{ m.s}^{-1}$ ) flow fluctuating between north and east. These conditions prevail till the passage of the sea breeze front approximately at 9h30 when wind turns to west. Wind speed starts to increase reaching a maximum of  $6 \text{ m.s}^{-1}$  at 16h. Temperature evolution is marked by a stabilisation at  $24^\circ\text{C}$  between 12h and 17h.

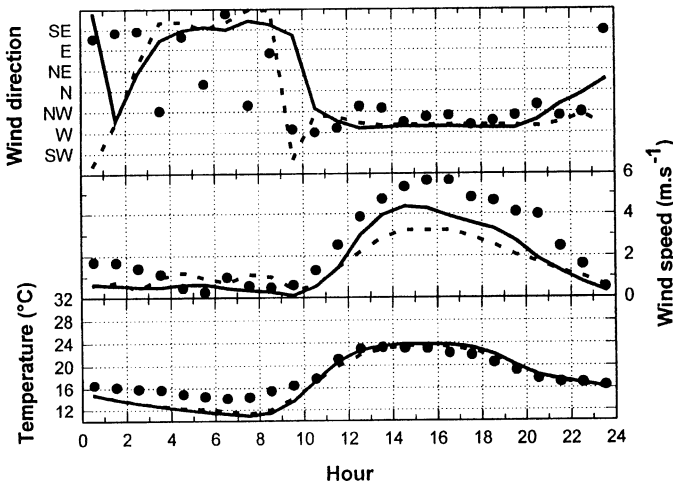


Figure 2 : Temporal evolution of meteorological data in Cacia (● meteorological data; — local scheme; --- TTT scheme).

Modelling results follow this pattern relatively well, revealing small differences between the two turbulence schemes. In Cacia, as well as in other stations [5] it was observed that major differences between the simulations occur when the wind speed is very low. Figure 2 also shows that the initial forcing is interpreted differently in both schemes, but after two hours of simulation this effect can be neglected. The local scheme develops a stronger wind during the afternoon without reaching maxima observed in the meteorological measurements. The cooling effect of the sea breeze is very well depicted by the simulations.



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### 3.4 Dispersion results

In order to investigate the effect of the turbulence scheme on atmospheric pollutant dispersion, a simulation including the release of a passive pollutant was performed. Figures 3 and 4 show the North-South vertical cross section

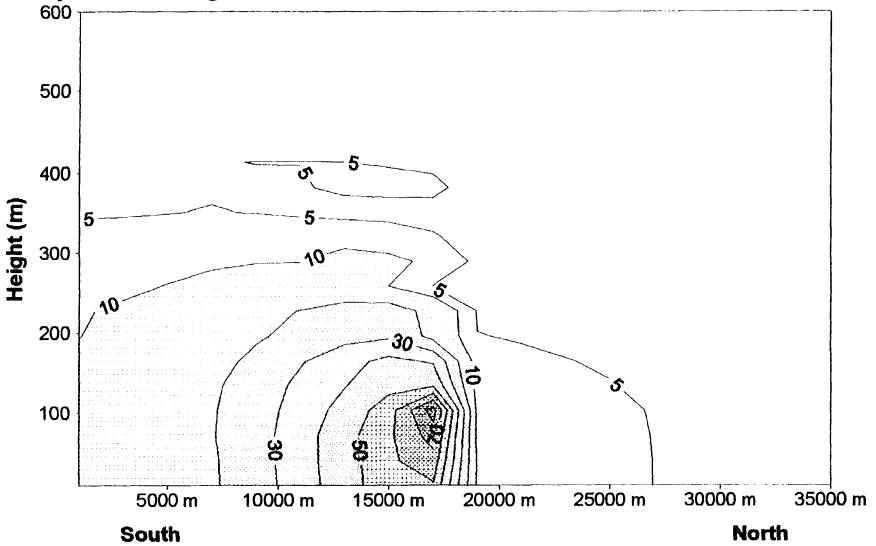


Figure 3 - Vertical profiles of pollutant concentration ( $\mu\text{g.m}^{-3}$ ) at 11h, in the North-South direction calculated by MEMO with the local turbulence scheme.

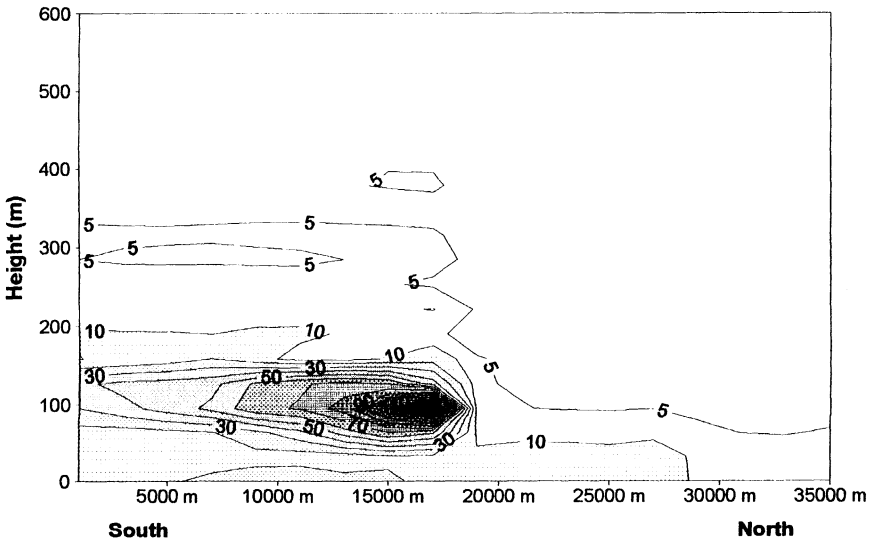


Figure 4 - Vertical profiles of pollutant concentration ( $\mu\text{g.m}^{-3}$ ) at 11h, in the North-South direction calculated by MEMO with the TTT scheme.

concentration distribution at 11h, respectively with the local and TTT scheme. Main component of wind was from North to South. Comparison between pollutant plumes represented by Figures 3 and 4 evidentiates different turbulent characteristics of the atmosphere.

The local scheme simulation shows a plume suffering a fumigation process. Ground level concentrations reach  $50\text{--}60\ \mu\text{g}\cdot\text{m}^{-3}$  at 2-5 km from the source. Meanwhile, the TTT scheme calculates a plume trapped in a stable layer. Maximum ground level concentrations of  $20\ \mu\text{g}\cdot\text{m}^{-3}$  occur between 4 and 14 km from the emission point.

Comparison of the evolution of temperature vertical profiles might explain the differences encountered in the dispersion simulations. Figure 5 shows the vertical profile of potential temperature at 9h, 11h, 13h and 15h. This figure also includes the temperature profile measured in Aveiro at 15h35. Apparently the TTT scheme develops a stronger superadiabatic lapse rate in the surface layer consistent with the observations. TTT profiles indicate a gradual development of the boundary layer as the morning progresses, compared to the

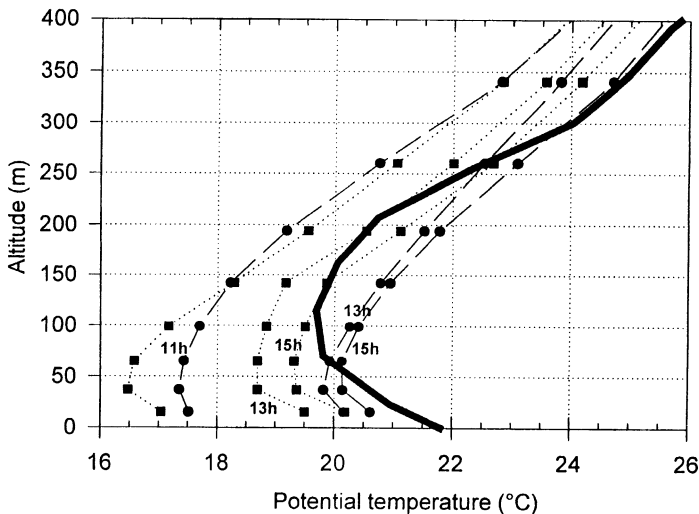


Figure 5 - Evolution of potential temperature vertical profile in Aveiro from 11 to 15h (—: radiosonde at 15h; ■: TTT scheme; ●: local scheme)



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local scheme which suggests a faster evolution from 11 to 13h. These results are consistent with other applications of TTT performed by Alapaty and Pleim [7].

### 4 Conclusions

Surface meteorological fields calculated by MEMO do not seem to be strongly affected by the introduction of the transilient parameterization. Nevertheless, application of MEMO to the study of passive pollutant dispersion suggests that the adoption of the transilient scheme causes significant changes on the dispersion patterns calculated by the model.

Differences encountered in the two simulations might be explained not only by the effect of the turbulence scheme but also by the parameterization of the surface fluxes. Careful analysis of surface fluxes parameterization will be performed in future papers.

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