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A SCALE-AWARE METHOD FOR PARAMETRIZING DISPERSION BY UNRESOLVED MESOSCALE MOTIONS IN THE ATMOSPHERE

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Abstract: Atmospheric dispersion models employed for regional and global transport of aerosols and gases typically rely on meteorological data from Numerical Weather Prediction (NWP) forecast models, usually archived at intervals ranging from 1 to 12 hours. Nevertheless, the atmosphere experiences high-frequency variability of winds due to mesoscale and microscale flows, including orographic flows, sea breezes, frontal circulations, boundary layer turbulence and moist convection. These processes generate rapid changes in wind speed and direction which may not be adequately captured in archived meteorological data due to the coarse temporal and spatial resolutions of NWP output, but still play a large role in atmospheric dispersion. To circumvent the challenge of generating and storing extensive NWP output, an alternative approach involves representing transport processes occurring at unresolved temporal and spatial scales within the dispersion model itself. The influence of sub-grid processes on the larger scale can be statistically accounted for in dispersion model parametrizations. It is important that these parametrizations cover the correct scales of motion such that all scales are represented through either parametrization or the NWP data, but that no motions are both resolved and parametrized.

A spectral analysis method is used to compare NWP horizontal wind data with boundary layer observations to determine the scales of motion unresolved in the NWP data. Velocity variances and Lagrangian timescales of the unresolved motions are calculated and the impact of meteorological conditions and location on the parameter values are investigated. These parameters can then be used to inform the parametrizations for the unresolved motions in the UK Met Office's operation dispersion model, NAME (Numerical Atmospheric-dispersion Modelling Environment), with the aim of developing a scale-aware parametrization that varies with NWP spatial and temporal resolution.

Key words: *Unresolved motions, mesoscale motions, parametrization*

INTRODUCTION

Atmospheric dispersion models for regional and global transport are usually driven by meteorological data from NWP (Numerical Weather Prediction) forecast models. These data will resolve motions down to a certain scale depending on the resolution of the NWP model, but the smaller, unresolved motions still play a large role in the dispersion (Gupta et al., 1997), so the effects of smaller motions are parametrized in the atmospheric dispersion model. In the dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment), there are two such parametrizations; a three-dimensional parametrization for the turbulence and a two-dimensional parametrization for the larger scale motions that we call the unresolved mesoscale motions. The latter parametrization accounts for the motions that are larger than those represented by the turbulence parametrization, but still smaller than what is resolved by the NWP data. It is important that this parametrization covers the correct scales of motion such that all scales are represented through either parametrization or the NWP data, but that no motions are both resolved and parametrized. As the scales of motion resolved in the NWP data will depend on both the spatial and temporal resolution of the archived NWP data (Webster et al., 2018), this unresolved mesoscale motions parametrization needs to be adjusted according to the driving meteorology and this is currently implemented in NAME by choosing an appropriate velocity variance and Lagrangian timescale. It is assumed that turbulence is not resolved in the NWP data so this parametrization can either be on or off without the ability to adjust the scales of motion represented in it.

Typically, scales of motion are described in terms of the characteristic diameter of the eddies and the time it takes for a parcel of air to be transported by the eddy. Atmospheric dispersion models use two parameters to determine the scales of motion unresolved in the NWP model; the velocity variance, σ^2 (m^2s^{-2}), which represents the spread of velocities around the mean velocity due to mesoscale motions, and the Lagrangian timescale, τ (s), which represents the characteristic timescale over which the flow properties change due to mesoscale motions.

These are used to inform the parametrizations for the unresolved motions in the dispersion model.

METHODOLOGY

Producing the spectrum of a time series of horiztonal wind data gives us the opportunity to evaluate motions on different timescales separately. Comparing the spectra from time series of observed winds to time series data for the same time period and location from an NWP model will show the differences between the two at varying frequencies of motion. We can then focus on the higher frequencies where the NWP data is no longer capturing the variance seen in the observed data due to unresolved motions.

Figure 1 shows an example comparison of the spectra of observed horizontal winds with that of NWP data. In this case, we use data from the Met Office's regional UKV model with the data on a 1.5km horizontal grid. We consider instanteneous horizontal winds archived at both 15 minute and hourly temporal resolution.

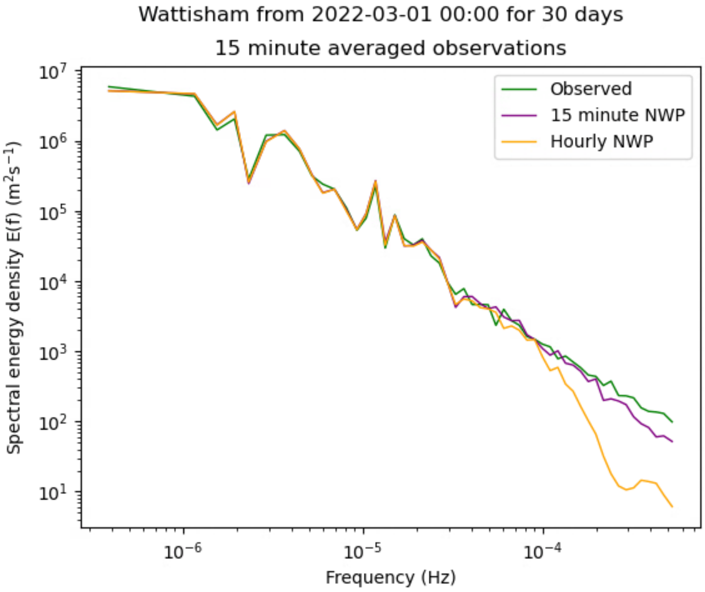

Figure 1. Spectra of the horizontal wind fields of observed 15 minute means (green), UKV 15 minute NWP data (purple) and UKV hourly data (orange).

Calculating velocity variances and Lagrangian timescales

The area beneath the spectral curve is the variance of the motions. As we are interested in only the variance of the missing motions, this can be calculated from the area between the spectra generated from the observations and from the NWP data.

The second parameter needed for the unresolved mesoscale motions parametrization is the Lagrangian timescale of the missing motions, τ. This is the typical time scale of the motions to be represented by the parametrization. We can find this parameter from the generated spectra by considering the correlation function of the missing motions. This correlation function is calculated by taking the inverse Fourier transform of the difference between the model and observed spectra. Assuming the missing motions are a first order autoregressive process (Webster et al., 2015), we can take the form of the correlation function, R_m, to be

$$R_m = \sigma^2 \exp\left(\frac{-t}{\tau}\right). \tag{1}$$

The Eulerian time scale is the time at which the normalised correlation function equals e^{-1}. Figure 2 shows an example of this correlation function with the dashed line showing e^{-1}.

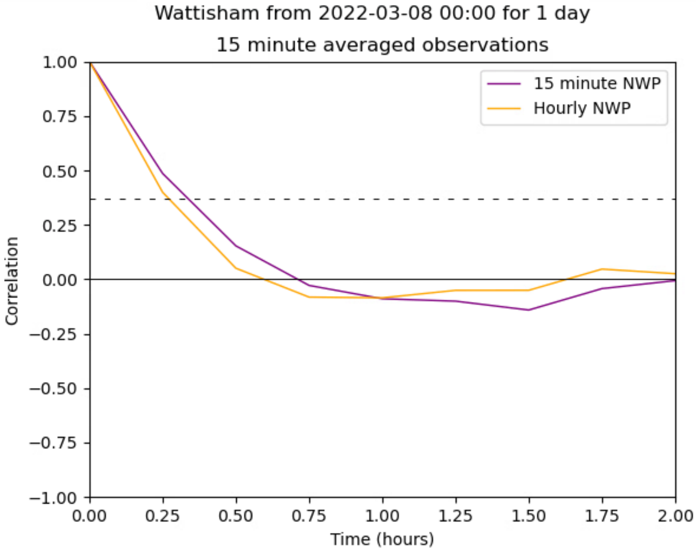

Figure 2. Correlation function of the unresolved motions for high temporal resolution (15 minute) and low resolution (hourly) NWP data from the UKV model (1.5km horizontal resolution). e^{-1} is shown by the dashed line.

Finding the point at which the correlation function reaches e^{-1} gives the Eulerian time scale, τ_E, as the observations and NWP data are from a fixed point in space. As NAME is a Lagrangian model, it is the Lagrangian time scale, τ_L, that is needed for the parametrization. Theory suggests (Hanna, 1981) that the relationship between the Lagrangian and Eulerian time scales can be given by

$$\frac{\tau_L}{\tau_E} \propto \frac{u}{\sigma}$$

For simplicity, we wish to have a single value for the timescale that does not depend on the wind speed u and we take $\tau_L/\tau_E = \beta$ where β is a constant. From observations, we can use $\beta = 3$ (Webster et al., 2015).

PRELIMINARY RESULTS

Currently, in the dispersion model NAME, the velocity variances and Lagrangian timescales of the mesoscale motions are parameters provided to the model. These parameter values must be manually adjusted according to the spatial and temporal resolution of the NWP data driving the model. Instead, we wish to develop a scale-aware parametrization wherein appropriate velocity variances and Lagrangian timescales are calculated directly within the dispersion model.

In order to create a scale-aware method for parametrizing the effects of unresolved mesoscale motions, we must first determine any factors other than the NWP data resolution that have an impact on the velocity variances and typical timescales of the missing motions. For this, we use NWP wind fields from the UK Met Office’s UKV model, with a horizontal grid of 1.5km and output every 15 minutes, compared with 15 minute time-averaged observations from 7 sites across the UK. We consider any annual cycle and impact of mean wind speed or location on the two parameter values.

Lagrangian timescale

Calculating the Lagrangian timescales using daily time series over a year, we can group the values produced by location and by month. We find that the calculated timescales do not have a clear trend throughout the year or by location. We also consider the impact of the mean wind speed during the period used to calculate the Lagrangian timescales, as shown in Figure 3. This suggests there is no depence of tau on the mean wind speed. Conceptually, the Lagrangian timescale is describing the ”size” of the missing motions, which we can expect to change with NWP resolution but should not be affected by meteorological or site conditions.

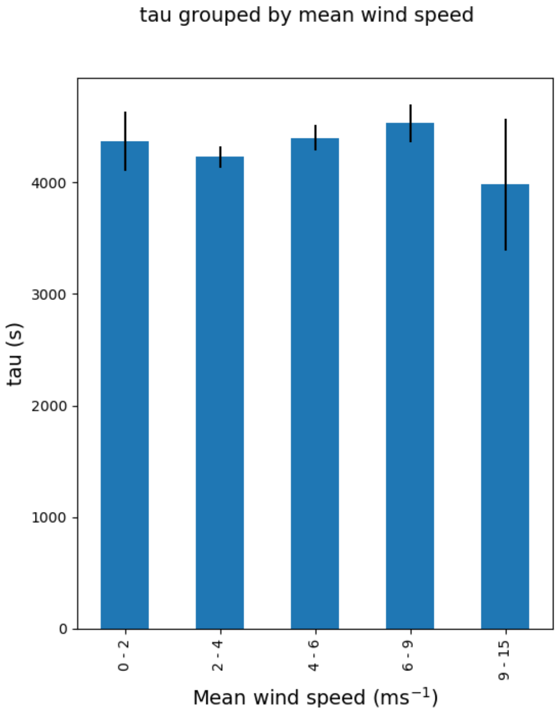

Figure 3. Mean Lagrangian timescale (tau) values grouped by mean wind with the standard error shown in black. Tau values are calculated from daily time series of 15 minute UKV NWP data compared with observed 15 minute means throughout the year 2022.

Velocity variance

As shown in Figure 4, grouping the velocity variances by mean wind speed, we see an increase in the typical velocity variances of the unresolved motions as the mean wind speed increases. As the typical velocity variances of the missing motions not only depend on the scales of motion unresolved by the NWP data but also on the variance of motions within those scales of motion, we can understand why the velocity variances would be affected by meteorological conditions as well as the NWP resolution.

Considering velocity variances by month and by location, we see there is variation here that is likely largely influenced by typical mean wind speeds also varying throughout the year and by location, although these results need further investigation at this time.

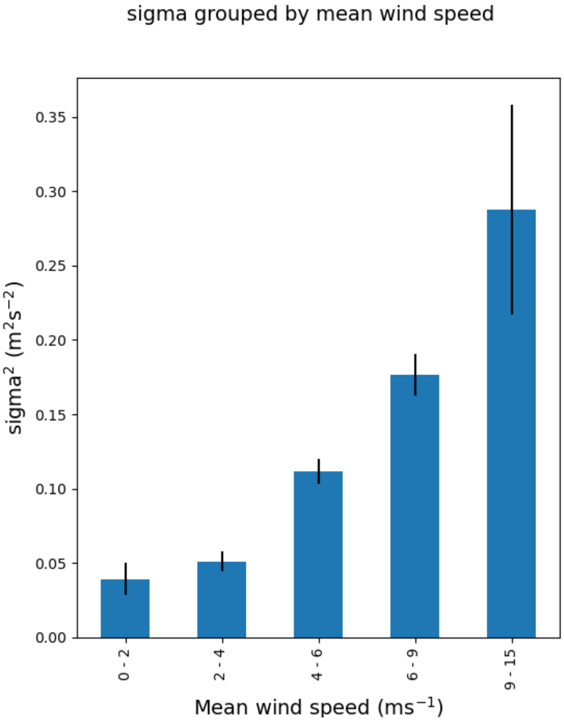

Figure 4. Mean elocity variance (sigma) values grouped by mean wind speed with standard error shown in black. Sigma values are calculated from daily time series of 15 minute UKV NWP data compared with observed 15 minute means throughout the year 2022.

CONCLUSIONS AND FUTURE WORK

In order to appropriately parametrize the effects of unresolved mesoscale motions in atmospheric dispersion models, we first need to understand how the typical Lagrangian timescale and velocity variance of these motions vary. It is clear the motions unresolved by the NWP model will depend on the model resolution, but before a relationship for this can be found, we first need to understand other factors that may affect these unresolved motions. In particular, we consider the meteorological conditions in terms of the mean wind speeds. We find that the typical Lagrangian timescale of unresolved motions are independent of the mean wind speed but the velocity variance of these motions increase with mean wind speed.

It may be that this dependency could account for variations throughout the year and locations due to typical conditions at particular observation sites or season. We should also consider other factors that may play a role (e.g. boundary layer stability) before deriving a relationship between the resolution (both spatial and temporal) of the NWP data and the Lagrangian timescales and velocity variances of the unresolved mesoscale motions.

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