On-line Tracer Simulation with Signal Technique Using WRF model

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Abstract

Pollutants can be transported over a long distance before they deposit at the downwind receptor area. In order to design emission control legislation, it is very important to find the so-called source-receptor relationship that determines which sources contribute to a specified receptor and also how much one source contributes relative to the others. An on-line approach is superior to other tracer calculation algorithms to study pollutant transport in that the transport calculations are performed directly within the host atmospheric model as opposed to separately on model output. *The objective of this study is to develop a tracer Weather Research and Forecast (WRF) model, in which an on-line tracer calculation algorithm with signal processing techniques will be implemented into the WRF model.*

1. Method Description

An on-line tracer approach implements the conservation of a tracer equation into a meteorological model, where tracers are treated as the other scalars in the model. Tracers are emitted from origins of pollutants and are tracked during integration. This on-line approach can avoid both spatial and temporal interpolations of meteorological data which are the main error sources for the off-line trajectory method. In addition, this method can take the effects of subgrid-scale convective mixing and subgrid-scale turbulence mixing into account, consistently with meteorological scalars. One limitation of this method is that one pollutant species received at one receptor can come from different emission sources, it becomes computationally costly (in terms of both memory and time) within an atmospheric numerical model to find a unique source-receptor relationship if there are many kinds of pollutants emitted from many places.

To solve this problem, Hsu and Chang (1987) applied a signal technique to the on-line approach. In their experiments, a unique oscillatory pollution signal is superimposed onto emission data at each source point. The signal propagates with emission data through advective and diffusive processes in a simple numerical model. At the receptors, the frequency spectrum is obtained by analyzing the time series of pollutant concentration using Fourier Transform Analysis. Since each source point was tagged with a unique frequency of oscillatory signal, it is expected that the source-receptor relationship could be potentially identified from the spectrum at the receptor. Several experiments were carried out with linear and weak nonlinear transformation, and their results were very promising. However, their model is an idealized horizontal two-dimensional (2D) Eulerian numerical model, and a uniform flow of

20 ms^{-1} was used. To further evaluate the technique, more studies using a realistic and sophisticated atmospheric model will be required.

Tracer transport is mainly determined by the wind and the instability of the atmosphere. The nonlinearity of the wind field is an important characteristic of the real atmosphere. Therefore, the signal transport in the real atmosphere can be very different from that of the simple, constant-wind 2D model in Hsu and Chang (1987). Thus, we will use WRF model, a fully compressible 3D non-hydrostatic model with higher order accuracy numerical schemes, to investigate this signal technique.

2. Experiments and Results Analysis

We choose the idealized 3D supercell case for this study. The tracers with signals were released into the model at the chosen source points. The model domain had 100 grid points in both x and y directions, with a horizontal grid spacing of 2 km. The vertical direction used 41 layers, with the top boundary at 20 km. The 1.5 order TKE subgrid-scale eddy diffusion and Purdue microphysics schemes were used. A time step of 10 s was used and the model integrated for 1 day.

a. Selection of source and receptor locations

Figure 1 shows the wind field at the first model layer, which is approximately 30 meters above the surface. Based on the wind field, which is crucial for the transport direction of the tracer and signals, 4 sources and 3 receptors were chosen, as shown in Fig. 1b.

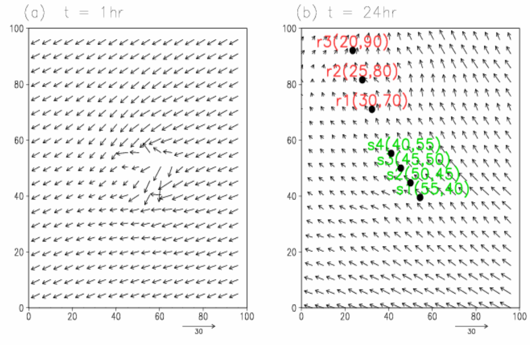

Fig.1. Wind field plotting for the first layer: (a) after 1 hour (b) after 24 hours. The 4 dots with green letters in (b) are the 4 source points chosen for the later experiments, and the 3 dots with red letters are the receptor points.

b. Signal experiment

The model was rerun with signals emitted from the chosen emission locations. The background concentration was set to zero. Five tracers were released into the model a half day after the model initial time to avoid the spurious short waves that existed in the first few hours. Tracers one to four were placed at the four source points at a constant rate to represent constant emissions. Every emission location also released a unique oscillatory signal, corresponding to the individual tracer, and all four (i.e., s1 to s4) were carried in Tracer 5. All signals had the same amplitude. The signal frequencies for s1 to s4 were 21, 31, 39 and 47 cycles per day (cpd), respectively. The receptors (i.e. r1-3 in Fig. 1b) were chosen downstream of the four tracer emission locations. The time series of Tracer 5 were analyzed at these receptors, and compared with the results of Tracers 1 to 4.

Fig.2 shows the 1-day time evolution of the concentration of Tracers 1-4 received at r1 (30, 70) and r3 (20, 90). Ideally these receptors should also receive corresponding signals carried by Tracer 5 during the simulation if they are not damped out or aliased.

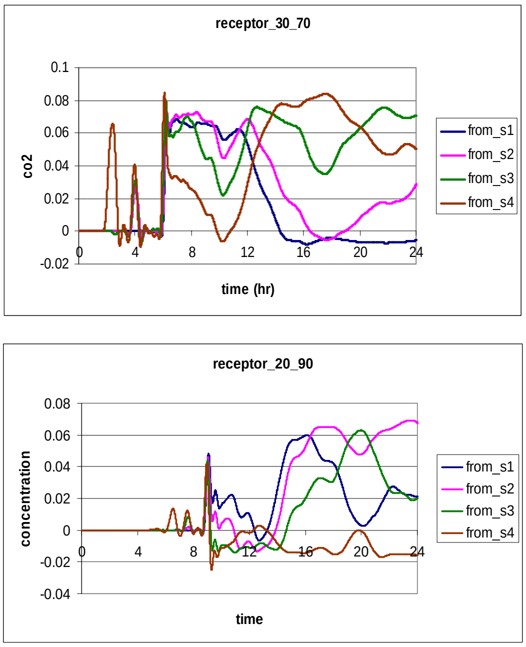

Fig.2. Time evolution of the concentration of Tracers 1-4 received at r1 (30, 70) and r3 (20, 90)

Figure 3 shows the power spectrum plot at r1 and r3. For the receptor r1, the four distinct peaks are corresponding to the frequencies of 22, 31, 39 and 47 cpd released from s1 to s4, respectively, as shown in the tracer plot in Fig. 2a. For the receptor r3 (20, 90), the spectrum has three clear peaks and they correspond to the frequencies of 22, 32 and 40 cpd. This is evidenced by the tracer plot in Fig. 2b. The magnitude of Tracer 4 has become too small after arriving at r3 and almost could not be detected in the spectrum analysis. There was a slight shift for these three frequencies because of the nonlinear interaction between wind fields and signals. Since these shifts are much smaller than the interval of two successive signals, the signals are still distinguishable. The signals received at both receptors are consistent with tracer simulations.

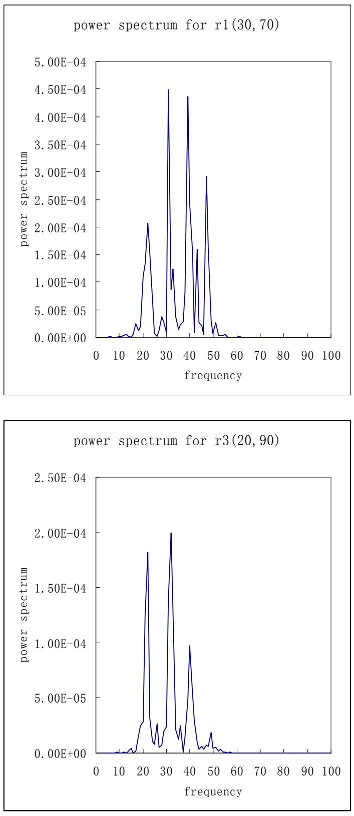

Fig.3. Power spectrum plot of r1 (30, 70) and r3 (20, 90) for the 1.5 day experiment

Next, the results were analyzed using STFT to get the detailed frequency information for different time segments. A four hour time window was chosen, and half-lapping was applied, thus there were 11 windows for the total one day period. Fig. 4 shows two STFT windows' power spectrum plots for the receptor r1. The power spectrum analysis of window 4 has three peaks at frequencies 23, 33 and 42 cpd, corresponding to signals released from s1 to s3, respectively. The power spectrum analysis of window 9 has two peaks at frequencies 39 and 48 cpd, which correspond to signals released from s3 and s4, respectively. Between hour 6 and 10 at receptor r1, the concentration from Tracer 4 is much smaller than those from the 3 other sources; while from hour 16 to 20, the concentrations of Tracers 1 and 2 are almost negligible compared with those of Tracers 3 and 4 (Fig. 2a). Thus the results from the STFT anaysis are consistent with the tracer simulations.

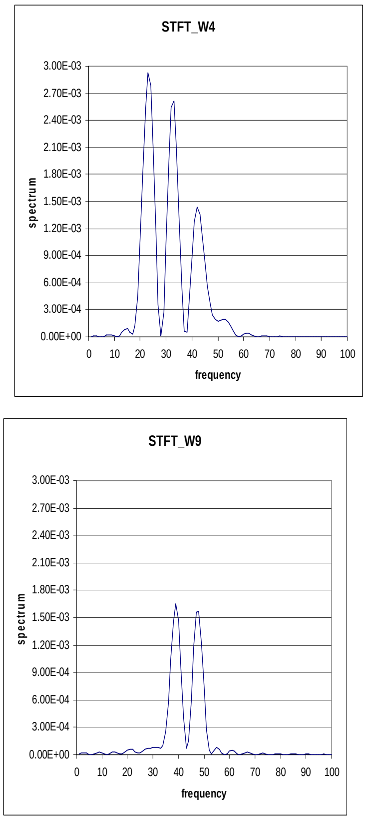

Fig.4 STFT plot for r1 (30, 70). The left panel is the 4th window, which is from 6 h to 10 h, and the right panel is the 9th window, which is from 16 h to 20 h.

3. Conclusions

The results from the signal experiments show that applying the signal technique to the online tracer WRF model could obtain similar source-receptor relationship as the one from the constant tracer case. As WRF model is realistic atmosphere model, whose simulation is very close to the real atmosphere, thus this signal technique has the potential to be applied to the real case and solve air pollution problems in the future.