Odour-impact assessment around a landfill site from weather-type classification, complaint inventory and numerical simulation

C. Chemel [a,*], C. Riesenmey [b], M. Batton-Hubert [b], H. Vaillant [b]

[a] *National Centre for Atmospheric Science, Centre for Atmospheric & Instrumentation Research, University of Hertfordshire, College Lane, Hatfield, Herts AL10 9AB, UK*

[b] *Centre SITE, ENS des Mines de Saint-Etienne, 158 cours Fauriel, 42023 Saint-Etienne, Cedex 2, France*

Abstract

Gases released from landfill sites into the atmosphere have the potential to cause olfactory nuisances within the surrounding communities. Landfill sites are often located over complex topography for convenience mainly related to waste disposal and environmental masking. Dispersion of odours is strongly conditioned by local atmospheric dynamics. Assessment of odour impacts needs to take into account the variability of local atmospheric dynamics. In this study, we discuss a method to assess odour impacts around a landfill site located over complex terrain in order to provide information to be used subsequently to identify management strategies to reduce olfactory nuisances in the residential neighbourhoods. A weather-type classification is defined in order to identify meteorological conditions under which olfactory nuisances are to be expected. A non-steady state Gaussian model and a full-physics meteorological model are used to predict olfactory nuisances for both the winter and summer scenarios that lead to the majority of complaints in neighbourhoods surrounding the landfill site. Simulating representative scenarios rather than full years make a high resolution simulation of local atmospheric dynamics in space and time possible. Results underline the key role of local atmospheric dynamics in driving the dispersion of odours. The odour concentration simulated by the full-physics meteorological model is combined with the density of the population in order to calculate an average population exposure for the two scenarios. Results of this study are expected to provide helpful information to develop technical solutions for an effective management of landfill operations, which would reduce odour impacts within the surrounding communities.

Keywords: Landfill site; Olfactory nuisances; Complex terrain; Data classification; Numerical simulation

* Corresponding author. Tel.: 441707286143; fax: 441707284208.
E-mail address: c.chemel@herts.ac.uk (C. Chemel).

1. Introduction

Municipal solid waste (MSW) is often disposed into landfill sites. A fraction of the landfill gases are emitted into the atmosphere. These gases are either originally present in the waste or formed during its decomposition process. Organic matter in the waste decomposes, while producing methane (~ 60 %), carbon dioxide (~ 40 %), and non-methane volatile organic compounds, referred to as VOCs (see for instance Brosseau and Heitz, 1994). Beyond major concerns related to environmental management, the greenhouse effect and health hazards, waste disposal units are potential sources of olfactory nuisances in residential neighbourhoods. Although biogas is usually collected and treated, and soil is covered to avoid emission, some of the landfill gases diffuse into the atmosphere, especially from the working face (typically ~ 20 %) (Spokas *et al.*, 2006). Among the gases released in the atmosphere, undesirable trace VOCs contribute to a large degree to poor air quality (*e.g.* Allen *et al.*, 1997; Kim *et al.*, 2005). In addition, biological heat may significantly modify the energy balance of the working face and may thus lead to an increase in the net energy flux (Bendz and Bengtsson, 1996).

Although odour pollution events may be attributed to increases in the emission of landfill gases (for instance due to special manipulation of the waste), these events are usually associated with 'stagnant' meteorological conditions with limited vertical mixing and low wind speeds, for which dispersion of odours is reduced. Landfill sites are often located over complex topography for convenience mainly related to waste disposal and environmental masking. Meteorological conditions are difficult to predict over complex terrain, and odour impacts are correspondingly difficult to assess.

Several studies have been conducted to identify and characterize relationships between meteorological conditions and impaired air quality episodes. Principal Component Analysis (PCA) and clustering techniques are commonly used to provide representative synoptic meteorological scenarios for air quality studies (*e.g.* Eder *et al.*, 1994; Greene *et al.*, 1999; Kim Oanh *et al.*, 2005). However, only a few studies discussed the application of such classification methods over complex terrain. As pointed out for instance by Berman *et al.* (1995), synoptic weather-type classifications only give the atmospheric conditions under which a local-scale study should be further conducted to understand local-scale dispersion of pollutants. Nanni *et al.* (2004) used a local-scale approach to sort data into predefined weather-type classes in an alpine region. Brulfert *et al.* (2006) used a similar technique in two alpine valleys, while proceeding from local- to synoptic-scale weather-type classes to sort data.

Dispersion models have become a common tool to evaluate the impacts of odour sources for given meteorological conditions (Yang and Hobson, 2000; McIntyre, 2000; Stuetz and Frechen, 2001). Most of the models that have been applied to odour-impact assessment are Gaussian models (Sarkar *et al.*, 2003). These models are usually not designed to account for the variable characteristics of the dispersion process as well as for complex terrain (*e.g.* Ormerod, 2001). Even if the near-field dispersion is for the most part driven by the meandering behaviour of the plume and not so much by turbulent processes, the unsteady turbulent behaviour of the atmosphere needs to be considered appropriately (see for instance Aubrun and Leitl, 2004). Non-steady state models were used to overcome this issue (*e.g.* Mussio *et al.*, 2001; Schauberger *et al.*, 2001; Tagaris *et al.*, 2003; De Melo Lisboa *et al.*, 2006). In addition, some non-steady state Gaussian models make it possible to deal with complex terrain, such as the Atmospheric Dispersion Modelling System (ADMS) (Carruthers *et al.*, 1994). However, the Gaussian approach is generally limited by simplified physics as well as a poor representation of the meteorological forcing.

The distinct objectives of our work are (*i*) to identify relationships between regional- and local-scale atmospheric dynamics and odour pollution events from a landfill site located over complex terrain, and (*ii*) to evaluate the value of both a non-steady state Gaussian model and a full-physics meteorological model in predicting population exposure to olfactory nuisances around the landfill site. The present study aims to provide relevant information to develop effective control or warning strategies with respect to olfactory nuisances in the nearby neighbourhood.

The outline of the paper is as follows. The landfill site and experimental data are presented in § 2. In § 3, PCA and clustering techniques are applied to both regional- and local-scale data in order to identify the weather types that favour odour pollution events around the landfill site. An overview of the Gaussian and meteorological models is given in § 4. In § 5, results from the models are discussed for the two weather types that lead to the majority of complaints in the vicinity of the landfill site. Conclusions and suggestions for further work are given in § 6.

2. Observational site and experimental data

Fig. 1

2.1. Site description

The landfill site is located North of the French Alps. It is surrounded westwards by the Massif Central mountain range and eastwards by the Rhône corridor. The site is embedded within a complex terrain at the foothill of the Pilat Regional Nature Park, which reaches an altitude of 1432 m above ground level (a.g.l.) (see Fig. 1). The waste is heaped up into a small valley. Three major towns (with populations in the range $10,000-25,000$ inhabitants) spread around the landfill site within a 5-km radius, and are denoted by RLM, LCF and FIR in the present study. The landfill site is one of the five largest French disposal facilities. The site receives more than 500 ktons of waste (mainly MSW) every year. The waste is composed of 50 % of solid household refuse, 40 % of non dangerous industrial waste, and 10 % of sewage sludge. The filling of the site started approximately 20 years ago and is expected to finish in about 15 years. The compacted waste is covered with a soil-covering, except the working face (*i.e.* the open cell), which encompasses an area of about 5000 m^2. Landfill leachate is collected and discharged into a collection and treatment system. Biogas is collected and burned to produce electricity. Since residential areas are located close to the site, manipulations of fresh waste over the open cell may lead to olfactory nuisances within the surrounding communities.

2. 2. Equipment and collection of data

A ground meteorological monitoring station is located in the landfill site area (see Fig. 1). Data from this station was recorded from 2002 and 2004, and includes pressure, temperature, relative humidity, wind speed and direction, and precipitation. The operational mode continuously samples these variables, using a 30-min acquisition cycle. A detailed complaint inventory (consisting of date, duration and location of olfactory nuisances) is available from 2002 to 2004 and contains a total of 71 complaints. Complaints were reported within a radius of about 5 km around the landfill site.

In order to identify the trace VOCs emitted by the landfill site and to quantify their emission rates, a field sampling was undertaken by TERA Technologies during workdays from 23 to 25 August 2005. The sampling site was located a few meters from the working face and the air was sampled at about 2 m above the ground. These days were typical of clear-sky summertime anticyclonic conditions. Sampling was carried out using sorbent materials (Tenax collectors). Each sample consists of an adsorptive tube which was loaded for 4 min using a pump at a rate of 0.1 L min^{-1}, then desorbed and analyzed for 10 min. A total of 125 samples were analyzed continuously in time (one sample every 14 min). VOC analysis was performed using an automated system including a preconcentrator. Samples were thermally-desorbed at 220 °C and transferred to a Gas Chromatography/Mass Spectrometry (GC/MS) system. The separation of the compounds was performed using either an OV-1 (polymethylsiloxane) or a Poraplot Q (styrene-divinylbenzene) GC column coupled with the MS, which covered the mass range 35–250 amu. A standard semi-quantitative analysis was carried out afterwards by comparing the compound mass spectra with those of a reference database.

Several VOC species were identified including including alkanes (*e.g.* heptane, decane), terpenes (*e.g.* α-pinene, limonene), aromatic compounds (*e.g.* toluene, xylene isomers), and chlorinated compounds (*e.g.* trichloroethylene, tetrachloroethylene). The trace VOCs emitted by the landfill site are comparable to those reported in previous studies (see for instance Allen *et al.*, 1997). Among these VOCs, toluene was selected as a typical trace VOC that is representative of the source under investigation and has a high emission rate (see also Davoli *et al.*, 2003). Assuming that emissions are fairly homogeneous over the area of the working face (assumption to be tested in future research), the toluene emission rate was calculated by multiplying the concentration of toluene by the volume flow rate. A ‘generic’ daily emission profile was derived by averaging toluene emissions over the period of the field sampling. The emission profile was smoothed using a 1-h running average and normalized by the maximum emission. The resulting emission profile (see Fig. 2) is used in § 5 to investigate the dispersion of odours around the landfill site.

Fig. 2

3. Weather-type classification

3. 1. Regional-scale approach

Table 1

As a first attempt to characterize typical atmospheric conditions around the landfill site, we have classified the weather types using synoptic-scale criteria. The data was retrieved from twice daily operational radiosoundings in Lyon (France). Lyon is located approximately 100 km North-East of the landfill site. The data were extracted in the range 500–850 hPa and includes the extrema of the potential temperature gradient at 00 Coordinated Universal Time (UTC), 12 UTC, and 24 UTC to characterize regional atmospheric stability, the difference between air and dew-point temperatures at both 500 and 850 hPa at 12 UTC to characterize precipitation, and the wind speed and direction at both 500 hPa and 850 hPa and averaged between 00 UTC and 24 UTC. A PCA algorithm (see for instance Lebart *et al.*, 1997) was applied to the data from 2002 to 2004. A standard multivariate statistical method was used to identify the linearly independent components, which explain data variability (*e.g.* Kim Oanh *et al.*, 2005). Missing data was not taken into account in order to prevent artificial data from being included in the pooling procedure. All the factors deduced from the PCA algorithm were found to be significant and were thus retained for the data classification. Ascending hierarchical classification and K-mean cluster analysis were applied to divide the dataset into classes.

The resulting regional weather classes are reported in Table 1. Eleven classes (weather types) were obtained. In order to discuss the relevance of these weather types with respect to odour nuisances, the number of complaints associated with each class is also indicated in Table 1. Two weather types induce more than 15 complaints per 100 days, whereas the other ones generate less than 7 complaints per 100 days. Interpreting the physical meaning of these results may be premature although two weather types represent the majority of the recorded complaints. Precipitation and wind speed seem to be the most explanatory variables. An undeniable feature is that precipitation alleviates the emission of odours and cleans the atmosphere. Also, the presence of wind partly determines the dispersion of odours, while no wind favours odour stagnation. Interestingly, the regional atmospheric stability of the air mass does not provide any additional information since complaints occur for all stability criteria. It is very likely that this parameter differs significantly at the landfill site and 100 km North.

This regional-scale approach suggests that one need to focus on clear-sky and calm-weather conditions, which favour odour pollution events. As pointed out for instance by Brulfert *et al.* (2006), local atmospheric dynamics determines to a large extent air quality over complex terrain. As a result, a weather-type classification would need to be developed by taking into account local-scale variables. In addition, the regional-scale approach is found insufficient since it does not provide any information about the location and the time period of the odour pollution events. Indeed, we found that the complaints that were recorded are somewhat evenly distributed during the day (Riesenmey, 2008). So, the weather-type classification needs to be refined by turning to a local-scale approach.

3. 2. Local-scale approach

Atmospheric dynamics around the landfill site results from the combined effects of synoptic-scale dynamics and local-scale dynamics induced by complex terrain. Local features induced by the topography such as valley and slope winds, and frequent temperature inversions (long-lasting during wintertime) have indeed a strong impact on air quality. Local-scale phenomena may either dilute or confine the air mass within the landfill site area. A methodology similar to the one at the regional scale was applied to data from the ground monitoring station. 9 local weather types were identified. Only the two most representative classes that lead to the majority of complaints are retained for the discussion. These classes are characterized by high-pressure systems with no wind in both winter and summer. The spatial and temporal repartition of the complaints for both local-weather types is displayed in Fig. 3. In winter most of the odour pollution events occur in the evening in FIR, whereas in summer they occur in the morning in LCF. Note that no complaint was recorded at night (between 2300 UTC and 0600 UTC). The results show only a weak contribution of the average temperature to odour formation. Conversely, no wind conditions often lead to olfactory nuisances. This is consistent with the regional-scale weather-type classification. Nonetheless, the two local-scale classes contain less complaints per 100 days (about 8.9 in summer and 7.9 in winter) than the two regional-scale classes, which contain the majority of complaints.

While regional data gives useful information about the probability of odour events and complaints, local data gives essential information about the location of the complaints in space and time. Moreover, we found that regional and local data has to be treated separately. Indeed, it turned out that an analysis using both regional- and local-scale data leads to ill-defined weather classes (Riesenmey, 2008). In fact, these classes do not provide as much information about the probability of odour events and complaints as the regional classes and about the location of the complaints in space and time as the local classes. This section underlines the important role of local (thermally-driven) winds on odour dispersion around the landfill site. Therefore, we may conclude that one must account for small-scale atmospheric processes to achieve accurate prediction of odour events in the vicinity of the landfill site. Fig. 3

4. Numerical tools

The data classification presented above enables us to assign each day to a class representative of a weather type. Hereafter we focus on the winter and summer classes from the local-scale approach. A representative day of each of the two classes was identified as the closest to the barycentre of the point cloud points in the input variable space (Tirabassi and Nassetti, 1999; Sfetsos *et al.*, 2005). The days thus obtained are: 19 October 2002 for the winter class and 18 August 2002 for the summer class.

In the following, we evaluate the performance of both a non-steady state Gaussian model and a full-physics meteorological model to predict olfactory nuisances around the landfill site for the two days representative of the winter and summer scenarios. The prediction of the frequency of odour pollution events is very challenging since odour is a subjective information, which depends on human perception. The nonlinear relationship between odour intensity and odour concentration is usually described by empirical psychophysical laws (see for instance Sarkar and Hobbs, 2002). Nicell (2003) suggested dose-response relationships, which can be used to estimate contours of probability of response and degree of annoyance. In our study, we simply assume a bijective linear relationship between odour intensity and pollutant (or tracer) concentrations. As pointed out for instance by Termonia and Termonia (1999), it is unrealistic to explain the complex interaction and interference between all the compounds, which lead to the formation of odours. However, we may assess the impacts of odours that can be associated with a tracer of these odours. The dispersion of odours can thus be easily predicted using a dispersion model or a full-physics meteorological model. Thereafter, toluene is considered as a passive tracer for waste odour. The dominant tropospheric loss process is by reaction with the OH radical. The lifetime of toluene due to reaction with the OH radical is in the order of 2 days (Atkinson, 2000), so that it can be considered as a passive tracer on the time scale of a day or so. As indicated by Tagaris *et al.* (2003), for odorous species with high reactivity or short lifetime in the atmosphere, a chemistry-transport model should be used. The normalized emission profile of toluene displayed in Fig. 2 was used as a reference emission profile for both scenarios, even though it is representative of the summer class only. Odour emissions from the working face of the landfill site were assumed to cover one grid cell and were considered as area source emissions in both modelling systems.

4. 1. *The Gaussian model*

Numerical simulations were conducted using the ADMS model (see Carruthers *et al.*, 1994, for a description of the model). This non-steady state Gaussian model has been extensively used to investigate several case studies under various meteorological conditions as well as over complex terrain. The effect of complex terrain on the wind flow was taken into account by using the complex terrain module (Carruthers *et al.*, 1994). The model has already been applied to simulate the dispersion of odours (*e.g.* Hobbs *et al.*, 2000). The computations were performed on a 5 km $\times$ 5 km domain with a 100-m horizontal resolution. Such a high spatial resolution is required to faithfully account for dispersion at the local scale. The grid was centered over the landfill site area. The domain covers most of the area displayed in Fig. 1.

With respect to input requirements, data includes source characteristics (toluene molecular weight and molar heat capacity, emission rate and temperature), terrain properties (location, topography and roughness), and hourly surface meteorological data (pressure, temperature, relative humidity, wind speed and direction and precipitation). ADMS also requires as a bare minimum cloud cover, time of day and time of year. Note that the sky was clear during the two scenarios that were simulated, so that the cloud cover was set to zero. The model provides hourly ground surface concentrations over the whole computational domain. Note that ADMS does not provide any result when the wind speed is lower than 0.75 m s^{-1}, leading to a stagnation of odours in the model under such conditions.

4. 2. *The meteorological model*

The ARW (Advanced Research core of the Weather Research and Forecasting (WRF) model, Skamarock *et al.* 2008) model (simply referred to as WRF thereafter) was used to simulate the dispersion of toluene around the landfill site. We used the WRF/Chem add-on to the WRF model, which provides a capability for the modelling of the dispersion of tracers. The model was run on multiple grids using one-way nests down to a horizontal resolution of 100 m. Five nests using horizontal resolutions of 16 km, 4 km, 1 km, 300 m, and 100 m were used. The inner grid encompasses most of the domain in Fig. 1. The computations were made on 28 vertical levels up to 50 hPa. The grid was stretched along the vertical axis to accommodate a high resolution ($\sim$ 30 m on average) close to the ground surface. The averaged vertical grid spacing was about 500 m. For the two inner-most domains (using a horizontal resolution of 300 m and 100 m) we used high-resolution digital elevation, soil type, and landcover data at $\sim$ 10-m resolution. For the other domains and the other characteristics of the soil and the ground surface (*e.g.* monthly surface albedo), static data was derived from the default geographical data that is provided with the WRF preprocessing system.

Initial and lateral boundary conditions of the coarser domain were derived from the ECMWF (European

Centre for Medium-range Weather Forecasts) gridded analyses available every 6 h with a horizontal resolution of 0.5° on operational pressure levels up to 50 hPa for vertically distributed data, and surface and soil levels for surface and deep-soil data. A grid nudging technique (see for instance Stauffer and Seaman, 1990) was employed for the coarser domain during the first 6 h in order to constrain the model towards the analyses and to shorten the spin-up time. A relaxation zone covering 5 grid cells around each domain was employed to smooth gradients near the lateral boundaries.

For the simulations using a horizontal resolution greater than or equal to 1 km, we used the YSU nonlocal boundary-layer parameterization scheme (Hong *et al.*, 2006) for which sub-grid scale (SGS) mixing is classically parameterized within the scheme. This scheme assumes that there is a clear scale separation between the sub-grid and resolved scales, so that they can be treated separately. This assumption is not warranted as grid sizes approach a few hundred meters or less. Hence, for the finer-resolved domains using a horizontal resolution of 300 m and 100 m, we used a fully 3D local SGS parameterization scheme, namely the level-1.5 SGS parameterization scheme by Deardorff (1980). The Monin-Obukhov surface layer scheme was used to provide surface forcing in terms of momentum, heat, and moisture fluxes. The land-surface energy budget was calculated by the Noah soil-vegetation model (Ek *et al.*, 2003).

Other physics options that we used include the CAM3 radiation package (Collins *et al.*, 2006), the microphysical scheme by Thompson *et al.* (2004, 2006), and the ensemble cumulus scheme introduced by Grell and Dévényi (2002) for the coarser grids with a horizontal resolution larger than 4 km. Note that for the finer-resolved grids with a horizontal resolution of 1 km and less, convection was explicitly resolved (*i.e.* the cumulus scheme was switched off).

5. Results and discussion

5.1. Winter and summer scenarios

The meteorological model WRF was evaluated using observational data across the different nests. Results of the simulations were compared with both ground surface and vertically-distributed measurements. This evaluation is not detailed here since it is not the focus of the present paper. The nudging technique that was used did constrain the model to remain close to observational data. Figure 4 shows that the WRF model is able to capture very well the temporal variations in wind speed and direction at the location of the ground meteorological monitoring station for the summer and winter scenarios. In the present study, the strategy for further analysis was to select appropriate times of the day to optimally characterize dispersion around the landfill site. Hereafter, we decided to use 1000 UTC, 1400 UTC, and 1800 UTC. These times are representative of morning, afternoon, and evening conditions, respectively. The concentration of toluene at the ground surface, normalized by its daily maximum value, is displayed at these times in Fig. 5 for the winter scenario and Fig. 6 for the summer scenario.

Fig. 4

Fig. 5

Fig. 6

The dispersion of any atmospheric constituent is driven essentially by the wind field and atmospheric stability. It is noteworthy that the footprint of toluene emissions is clearly different in the ADMS and WRF simulations, especially at 1400 UTC and 1800 UTC. This suggests that the observations from the ground monitoring station that were used as input to ADMS might not be so representative for the area of interest. This can be explained by the station being located somewhat on the slope on the side of the small valley in which waste is piled up (see Fig. 1). At the location of the landfill site, a typical valley wind system develops. The wind is typically directed up the valley during daylight hours (*i.e.* daytime) and down the valley otherwise (*i.e.* nighttime). Up-valley winds are usually stronger than down-valley winds. This idealized picture of the flow does explain the location of the complaints for both scenarios. Indeed, most of the complaints occurred either in the early morning or in the evening (see Fig. 3).

The record of complaints reported by the community was analyzed along with results from both models. In that respect, WRF was found to outperform ADMS in predicting the location and timing of complaints. In particular, the plume of toluene simulated by ADMS does not move down the valley to FIR in the evening in both winter and summer, for which complaints were recorded (see Fig. 3). As mentioned above, this might be attributed to the observations from the ground monitoring station that were used as input to ADMS being not so representative for this area over complex terrain. Therefore, we decided to discard the results from ADMS to calculate a population exposure for the two scenarios.

5. 2. Population exposure

Environmental risk assessment is commonly applied in waste management (Pollard *et al.*, 2006; Butt *et al.*, 2008). Risks associated with potential health impacts from exposures to landfill gas and particulate matter receive increasing attention (*e.g.* Macleod *et al.*, 2006). Relating simulated odour concentrations to population exposure is key to assessing odour impacts around a landfill site (*e.g.* Sarkar *et al.*, 2003).

Fig. 7

The concentration of toluene at the ground surface simulated by WRF was combined with the density of the population. We defined population exposure as the product of the concentration and the population density, integrated over a period of time. This average exposure is calculated by dividing the integrated exposure by the time period of integration (see for instance Monn, 2001). The whole population was assigned to the built areas. The fraction of built area in each grid cell of the inner domain is displayed in Fig. 7. Most of the built areas lie in the valleys. Only a few habitations are located North-East of the landfill site.

The time integration periods coincide with the time periods used to optimally map the temporal repartition of the complaints for the two scenarios in Fig. 3, namely from 0600 UTC to 1000 UTC ($\sim$ morning), from 1000 UTC to 1500 UTC (∼ afternoon), and from 1500 UTC to 2300 UTC (∼ evening). Note that since perception of odour correspond to a much shorter time scale (on the order of a few seconds), the average exposure would considerably dilute short-term impact.

The average population exposure to odour pollution, normalized by its daily maximum value, is displayed for the abovementioned time integration periods in Fig. 8 for both the winter and summer scenarios. Consistent with initial indications from the WRF simulations, complaints are mainly to be expected in both winter and summer in the evening in FIR. Population exposure is much lower in the morning and in the afternoon during wintertime while being moderate in LCF in the morning and in FIR in the afternoon during summertime. Fig. 8

6. Summary and conclusions

The main goal of this study was to assess odour impacts around a landfill site located over complex terrain in order to provide information that could be subsequently used to identify management strategies to prevent olfactory nuisances in the residential neighbourhoods. This study consisted of several steps, as follows.

- Odour sources were identified during field sampling. The sampling was carried out on site in the vicinity of the working face to characterize the temporal fluctuations in emissions. Toluene was selected as a typical trace VOC that is representative of the source under investigation and has a high emission rate (see also Davoli *et al.*, 2003). A 'generic' daily emission profile (see Fig. 2) was derived by averaging toluene emissions over the period of the field sampling.
- Relationships between regional- and local-scale atmospheric dynamics and odour pollution events were identified by classifying weather types for the years 2002 to 2004. Data from operational radiosoundings was used at the regional scale while data from a ground meteorological monitoring station was used at the local scale. Data classification consisted of standard ascending hierarchical classification and K-mean cluster analysis to divide the dataset into classes (weather types). Our approach to weather-type classification is similar to the one used by Greene *et al.* (1999) and Kim Oanh *et al.* (2005). While being not surprising, we found that local data gives more information about the location of the complaints in space and time than regional data. As a result, small-scale atmospheric processes would need to be considered so as to achieve accurate prediction of odour events in the vicinity of the landfill site. The two most representative weather types that lead to the majority of complaints were characterized by high-pressure systems with no wind in both winter and summer. A representative day of each of the two weather types was identified in order to be simulated by both a non-steady state Gaussian model and a

full-physics meteorological model.

- Two days that are representative of the winter and summer scenarios were simulated with the ADMS and WRF models. The normalized emission profile of toluene was used as a reference emission profile for both scenarios. The footprint of toluene emissions was found to be significantly different in the ADMS and WRF simulations, especially in the afternoon and evening. The record of complaints reported by the community was analyzed along with results from both models. In that respect, WRF was found to outperform ADMS in predicting the location and timing of complaints. This might be attributed to the observations from the ground monitoring station that were used as input to ADMS being not so representative for this area over complex terrain. Indeed, the station is located somewhat on the slope on the side of the small valley in which waste is landfilled (see Fig. 1). As a consequence, we decided to discard the results from ADMS and use WRF to calculate a population exposure for the two scenarios. One has to bear in mind that advanced meteorological models (such as WRF) are usually not designed to be used in a friendly way by the user community. The methodology that we proposed based on a limited number of scenarios might be an efficient alternative to anticipate odour pollution events.
- The concentration of toluene at the ground surface simulated by WRF was combined with the density of the population in order to calculate a population exposure for the winter and summer scenarios. Since no census of the population was available at the local scale, we assumed it to be proportional to the density of built area. Consistent with initial indications from the WRF simulations, we found that complaints are mainly to be expected in both winter and summer in the evening in FIR. The 'risk' of complaint was much reduced in winter in the morning and in the afternoon. A moderate exposure was found in summer in LCF in the morning and in FIR in the afternoon. While the days that were simulated are representative of the winter and summer scenarios, they do not represent the whole range of meteorological conditions which can occur in these seasons. Still, results of this study are expected to provide helpful information to develop technical solutions for an effective management of landfill operations, which would reduce odour impacts within the surrounding communities.

One has to be aware of the limitations of the approach to odour assessment that we used. Odours are the result of a complex combination of several compounds. In our work we selected a single indicator compound (namely toluene) that is representative of the source under investigation and has a high emission rate. However, this might lead to an underestimation of the impact of odours since we tracked only one compound. It is unwise to superimpose the odour strength of several compounds with known odour strength in a multicomponent mixture. Indeed, individual odour components can mutually reinforce, weaken, or mask each other. The processes that drive the odour strength of the mixture require further investigation. Numerical simulations using a binary mixture might be a first step to refine and expand the present investigation. Source apportionment methods could also be used in order to analyze the contribution of various emission categories to population exposure.

The population exposure that we computed is integrated over time. However, short-term peak exposures can be significantly higher. One could also take into account characteristics of the microenvironments in which people spend their time by using information on their activities. In considering population activities, one could differentiate the population into age groups, young and elderly people being more sensitive to air pollution, or take into account geographical factors such as the location of schools or the proximity of hospitals. Another route to refine our analysis is to translate odour concentration into odour perception by using empirical laws such as those discussed by Sarkar and Hobbs (2002).

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Tables

Table 1. Description of the regional classes (weather types) and repartition of the complaints within the classes

Description of the regional classes				Number of		
Regional atmospheric stability	Risk of precipitation	Wind speed / direction		Days	Complaints (□)	Complaints per 100 days
		Above 1500 m	Below 1500 m			
Moderately stable	Very low	Very low / NA	Very low / NA	121	19 (2)	15.7
Unstable	Very low	Very low / NA	Very low / NA	89	14 (1)	15.7
Neutral	Low	Very low / NA	Very low / NA	182	12 (7)	6.6
Very stable	Low	Very low / NA	Very low / NA	113	7 (2)	6.2
Very stable	Moderate	Moderate / N	Moderate / S	105	5 (0)	4.8
Moderately stable	Moderate	Moderate / E	Strong / N-W	77	3 (2)	3.9
Moderately stable	High	Strong / N	Low / NA	104	4 (2)	3.8
Moderately stable	High	Moderate / S-S-E	Moderate / N-N-W	82	3 (1)	3.7
Moderately stable	Moderate	Moderate / S	Low / NA	72	2 (0)	2.8
Moderately stable	Moderate	Strong / E	Low / NA	81	2 (0)	2.5
Very stable	Moderate	Low / N	Low / NA	44	0 (0)	0.0

(□) *Complaints of olfactory nuisances that were identified as being related to special manipulations of waste* (e.g. *opening of a new cell).*

Figure Captions

Fig. 1. Orography of the landfill site area and its surroundings. The attached grey scale indicates altitude in meters above mean sea level (a.m.s.l.). Solid lines corresponds to major highways. The three major towns around the landfill site and the ground meteorological monitoring station located on the site are marked as ★ and ○, respectively. The stipple-filled area represents the exploited cells.

Fig. 2. Normalized daily profile of odour emission (—) derived from toluene concentration measurements close to the working face, averaged over the period of the field sampling. The profile was smoothed by calculating a running average of the raw data (∘) and by using a curve-fit procedure to get an analytical function.

Fig. 3. Same caption as Fig. 1. The clocks indicate the temporal repartition of the complaints for the local-scale winter (in white) and summer (in grey) classes, which contain the majority of complaints.

Fig. 4. Time series of wind speed (upper panel) and direction (lower panel), observed (• symbols) and predicted by WRF (solid lines) at the location of the ground meteorological monitoring station for the summer (in red) and winter (in blue) scenarios.

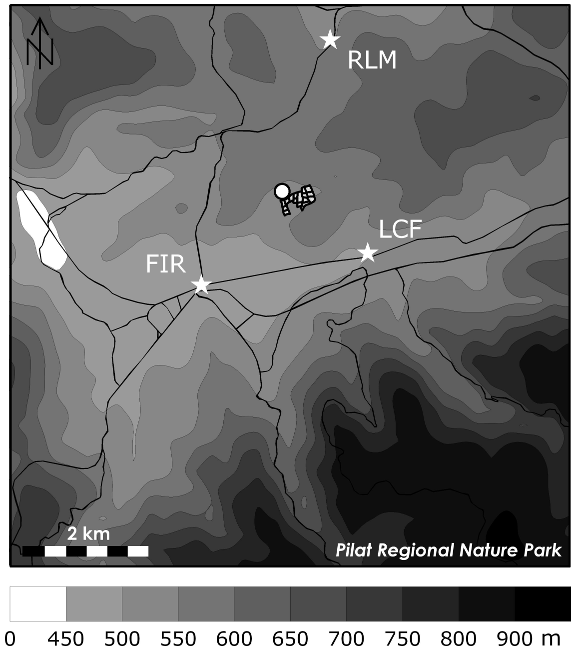
Fig. 5. Color-filled contours of the concentration of toluene at the ground surface, normalized by its daily maximum value, simulated by ADMS (left-hand column) and WRF (right-hand column) in the inner domain, at 1000 UTC ((*a*) and (*b*)), 1400 UTC ((*c*) and (*d*)), and 1800 UTC ((*e*) and (*f*)) for the winter scenario. The 10-m horizontal wind vector observed at the location of the ground meteorological monitoring station is superimposed on the ADMS plots. The 10-m horizontal wind vectors predicted by WRF are superimposed on the WRF plots. Solid lines indicate the topography with 10-m interval contours. Note that the extent of the domain is slightly different in ADMS and WRF because of different projection systems. The three major towns around the landfill site are marked as ★.

Fig. 6. Same caption as Fig. 5 for the summer scenario.

Fig. 7. Raster representation of the fraction of built area in each grid cell of the inner domain used for the WRF simulations. Solid lines indicate the topography with 10-m interval contours.

Fig. 8. Color-filled contours of the average population exposure to odour pollution derived from the concentration of toluene at the ground surface simulated by WRF in the inner domain and population density, for the winter (left-hand column) and summer (right-hand column) scenarios, integrated from 0600 UTC to 1000 UTC ((*a*) and (*b*)), from 1000 UTC to 1500 UTC ((*c*) and (*d*)), and from 1500 UTC to 2300 UTC ((*e*) and (*f*)). The average population exposure is normalized by its daily maximum value. Solid lines indicate the topography with 10-m interval contours. The three major towns around the landfill site are marked as ★.

Figures



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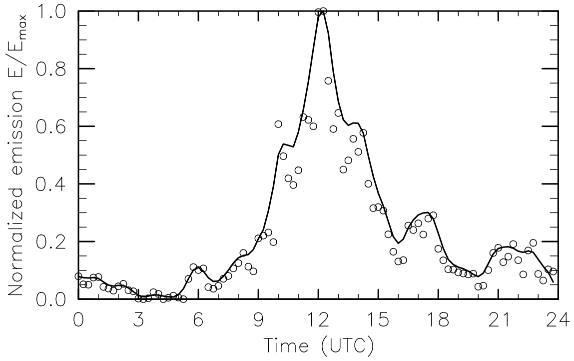

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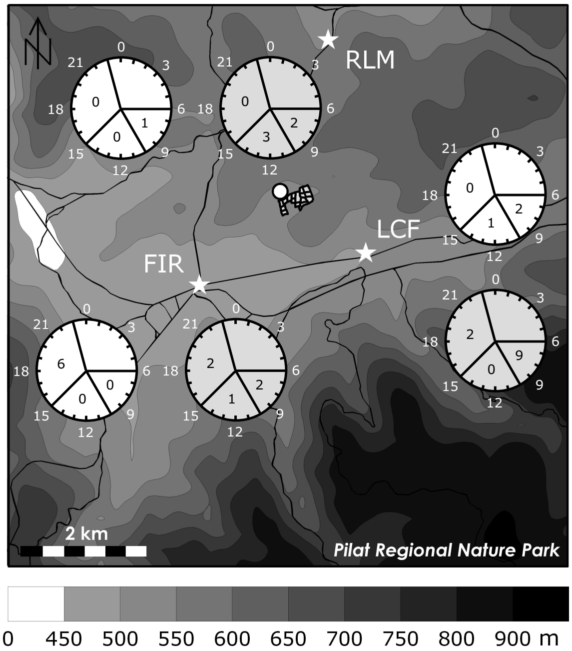

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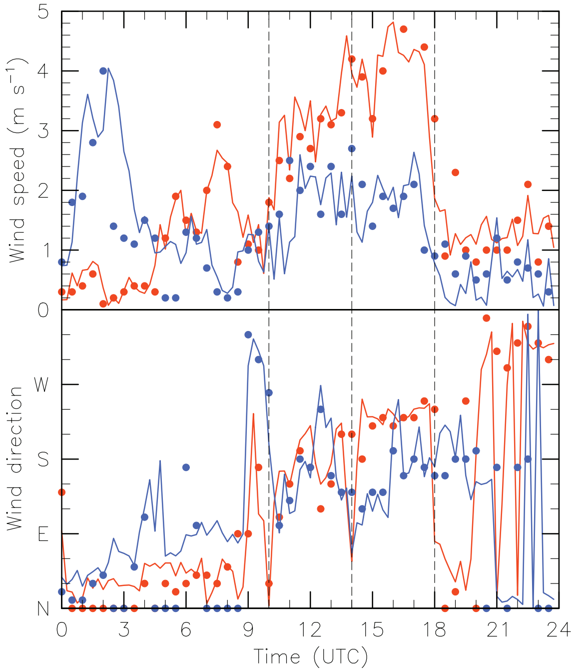

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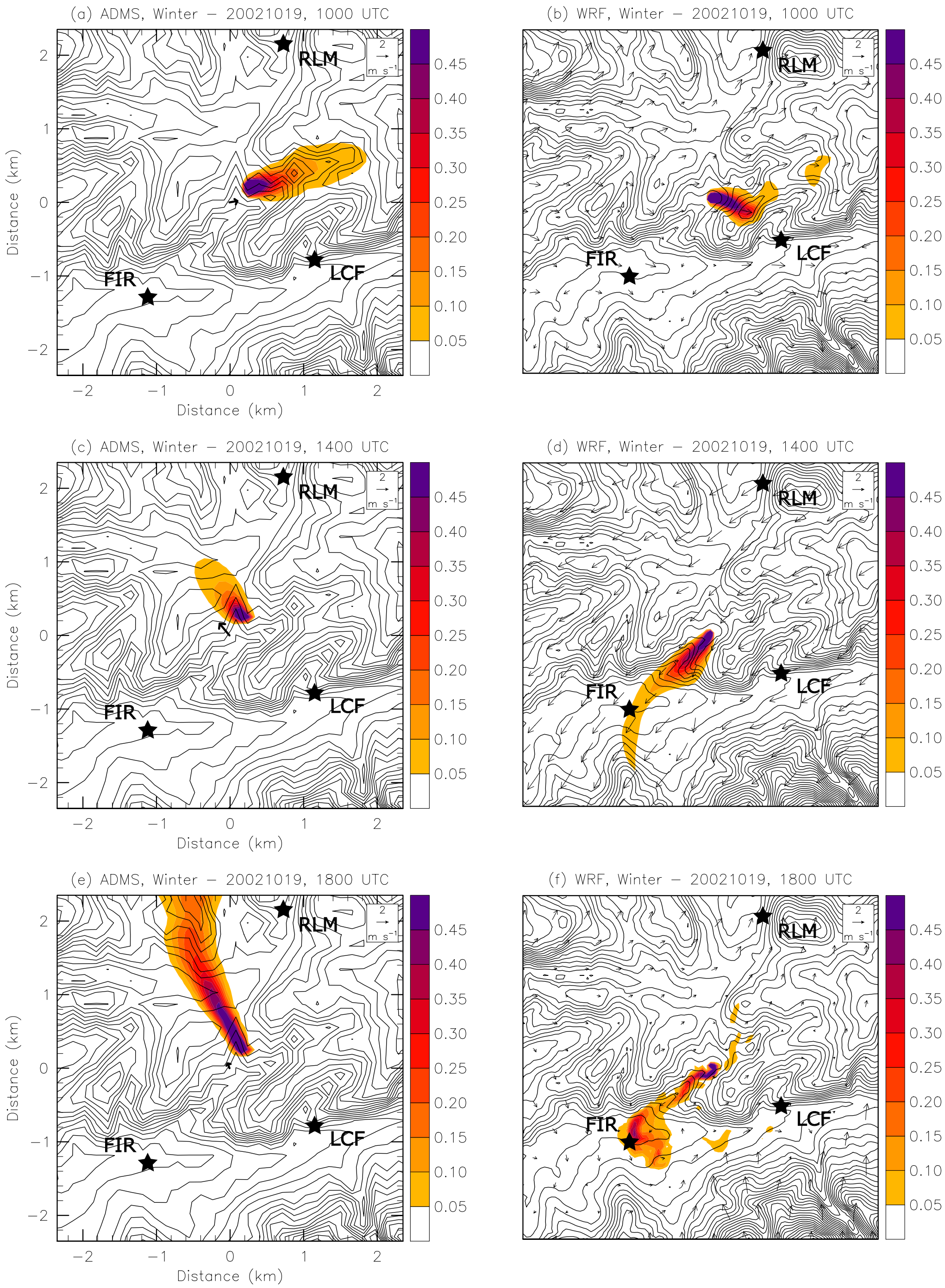

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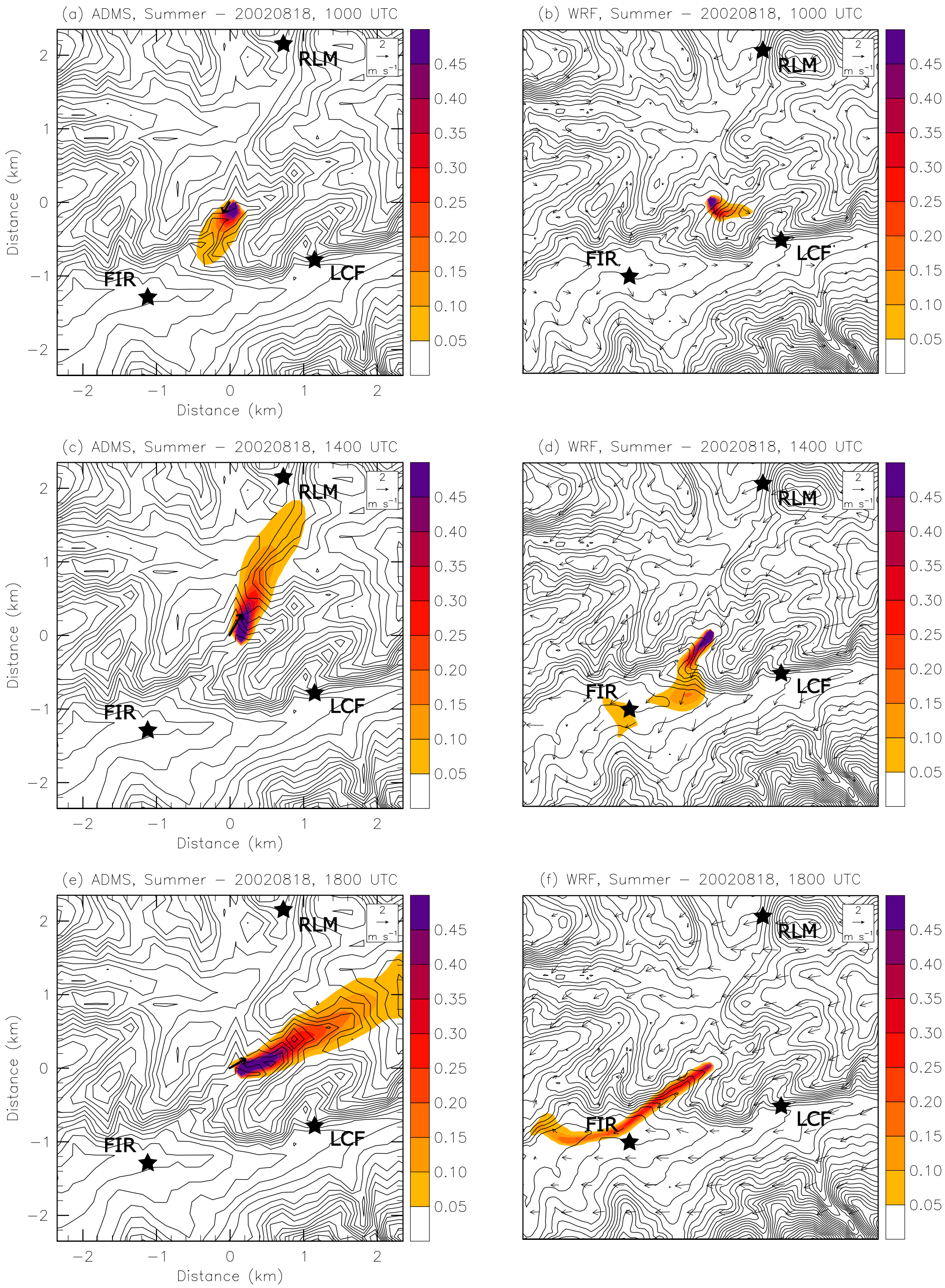

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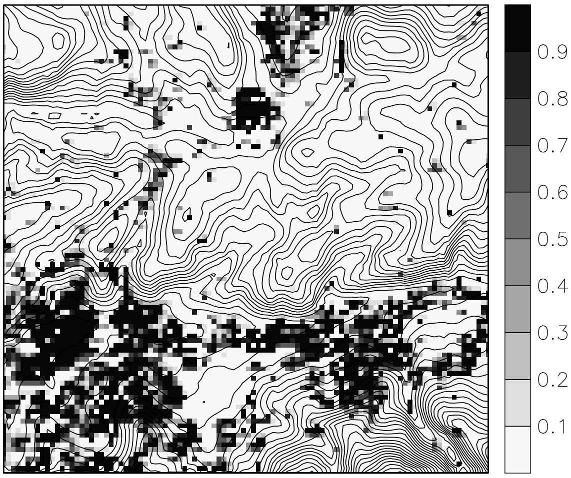

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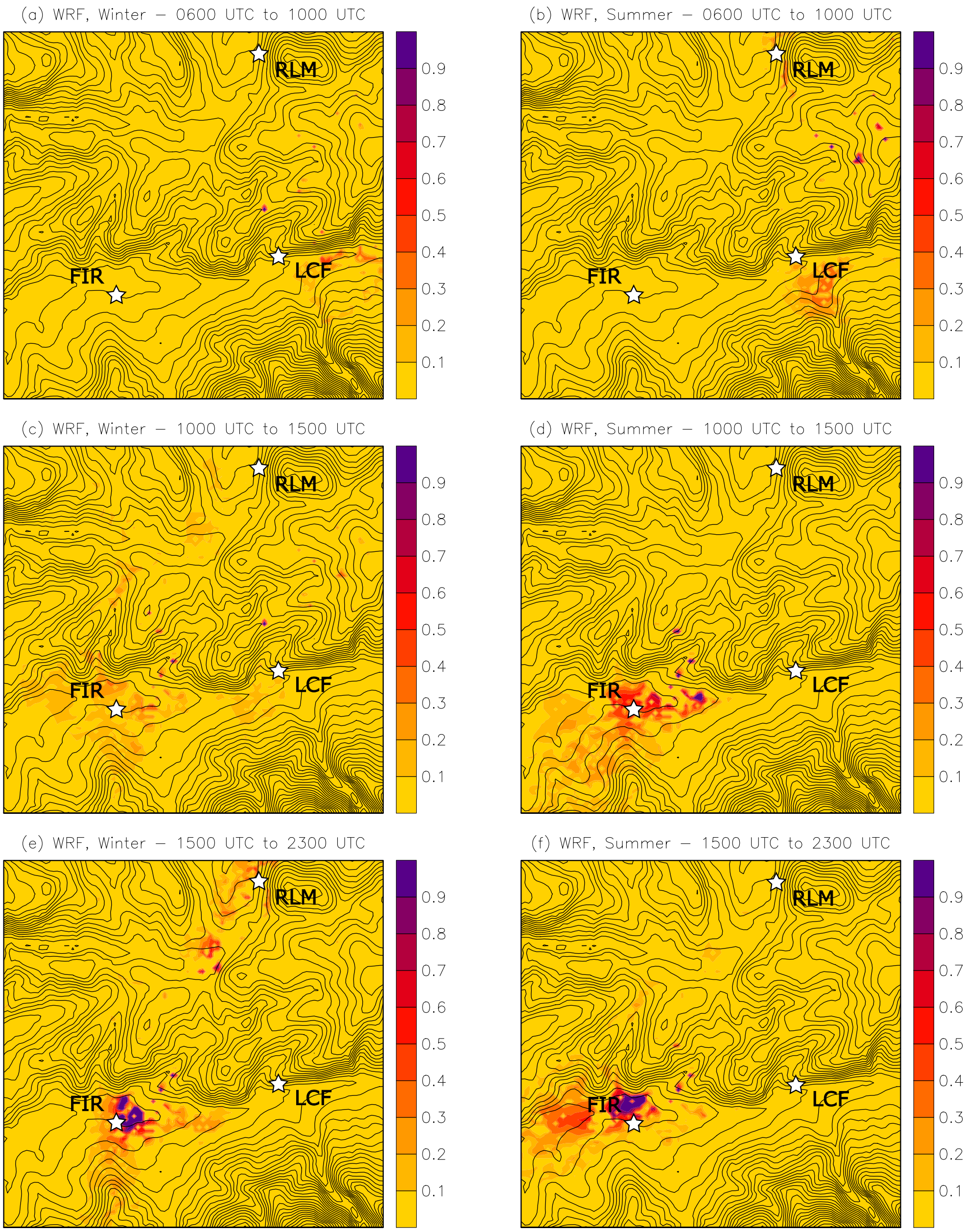

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