Aerosol and Air Quality Research, 16: 1473–1482, 2016
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ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2015.02.0112

Atmospheric Dispersion Study of TRS Compounds Emitted from a Pulp Mill Plant in Coastal Regions of the Uruguay River, South America

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ABSTRACT

The atmospheric dispersion of total reduced sulfur (TRS) emissions from the pulp mill plant of Fray Bentos, Uruguay is simulated. The local authorities of the Environmental Monitoring Program (EMP) of Gualeguaychú, Argentina, received social complaints of malodor presence in different places of the region. An atmospheric dispersion model coupled to a boundary layer forecast model is used to simulate 11 events in which the EMP officials attended the scene in order to verify the situation. The validation of modeled winds with the observations from a meteorological tower indicates reasonably accurate wind forecasts. The spatial layout of the modeled TRS plumes is compared with the geographical distribution of points in the area where the social complaints were recorded. Nine of the 11 studied events are successful modeling cases since a positive (negative) in situ verification matches with a plume position over (far from) the site. In one of the two unsuccessful modeling cases, although the plume is marginally distant from the site, the average wind direction error is the largest one of all the events. In the other case the modeled plume is in fact over the site, but the situation was negatively verified. The reason for the disagreement could be the wind direction changes during the event. This was the longest modeled case that lasted for 7 hours and the plume was meandering during that time; first from SSW to the S, then back the SSW, and finally to the S and SSE. The conclusion of the study is that, despite the inherent uncertainty of numerical simulations, the implemented modeling system shows versatility and proves to be a useful tool not only for diagnostic studies but also for preventing conflictive situations since it can produce reasonably accurate forecast of plume position and its potential impact.

Keywords: Atmospheric dispersion; Numerical models; Malodor events; TRS compounds.

INTRODUCTION

It is generally accepted that malodor perception responds to individual and subjective criteria, so that it is difficult to establish a universal standard of air quality. Therefore, a detection threshold for the malodorous substance is defined as the concentration value that must be overcome so that half the affected individuals detect the odor (EPA, 1990). The measurement of the malodorous substance concentration and its comparison with threshold values is the normal strategy used in the study of individual events. Atmospheric dispersion models are useful tools to determine the regional impact of malodorous compounds emitted from a point source. These models have been developed for a general use and cannot be directly applied to any situation. In occasions, to achieve valid and representative results in a particular case, a model must be adapted in order to study the transport and diffusion of malodorous substances in a given region.

As a consequence of the installation of a pulp mill plant in Fray Bentos, Uruguay (33°07’00’’ S–58°15’36’’ W, see “Fig. 1” for the location), there has been continuous social complaints in Gualeguaychú, Argentina, and neighboring regions, for the episodic occurrence of malodors. From 2008 (when the plant started the operations), to 2009 the number of complaints recorded by the local Environmental Monitoring Program (EMP) has increased. Since 2010 the events recorded have decreased and they are now more sporadic. The emissions of the pulp mill plant are characterized, among others, by a compound known with the name of total reduced

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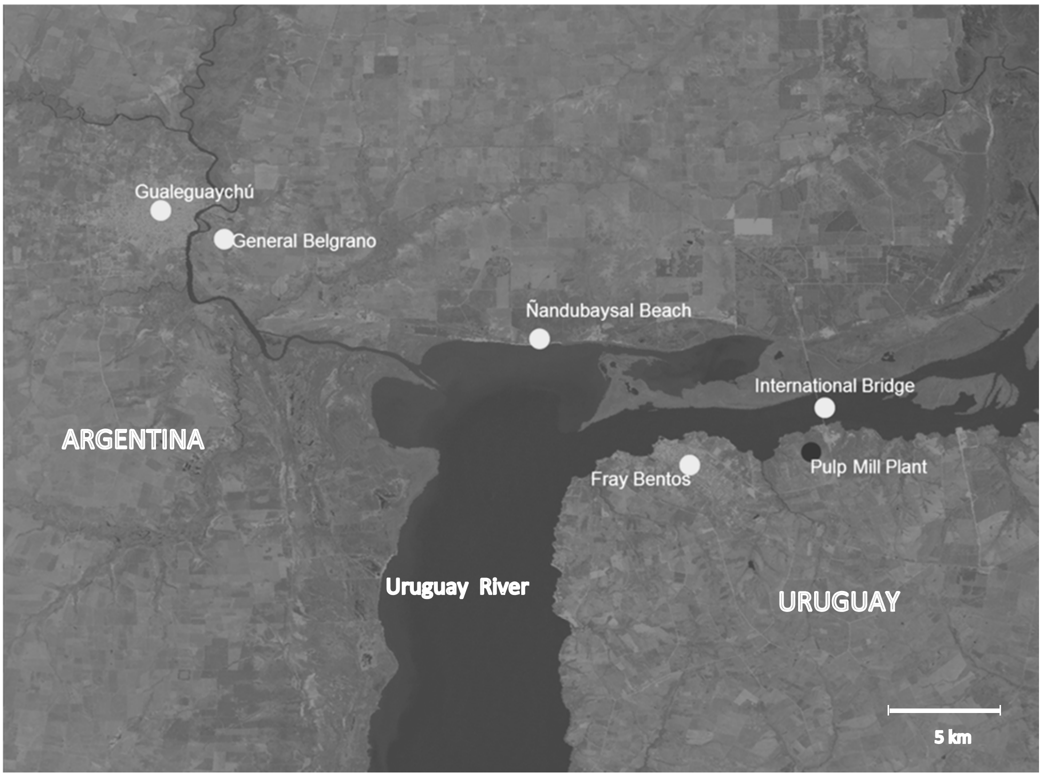


Fig. 1. Map of the region and location of the pulp mill plant.

sulfur (TRS), which is a group of substances that have a very characteristic odor, normally unpleasant and in occasions annoying, that can be detected at very low concentrations. These compounds are emitted in small amounts under conditions of normal operation, although in the occasion of a re-start of the plant the emissions can reach much higher values (Ecometrix, 2006). Atmospheric dispersion models can be used to simulate the transport and diffusion of the pulp mill plant emissions and calculate the resulting TRS concentrations. Thus, models become useful tools in environmental impact studies as they can be used for modeling particular situations and produce forecast that may allow preventing conflictive events.

This paper studies the atmospheric dispersion of TRS compounds emitted from the pulp mill plant of Fray Bentos, Uruguay, over the region of the Uruguay River near the border between Argentina and Uruguay. The present study is the first one that performs a series of experiments with an atmospheric dispersion model coupled to a boundary layer forecast model, for determining the dispersion of the TRS plumes emitted from the pulp mill plant. The modeled plumes are validated with the information recorded by the local authorities about the occurrence of malodors in the area. The transport and diffusion of TRS compounds is simulated with the Advanced Regional Prediction System (ARPS) model (Xue *et al.*, 2000, 2001), coupled to the Boundary Layer Model (BLM) that runs operatively at the National Meteorological Service of Argentina (Berri *et al.*, 2010, 2012). The spatial layout of modeled plumes and their TRS concentrations are compared with the geographical distribution of points in the area where the EMP officials received the complaints of the local population about the presence of malodorous substances. The objective of the study is to show that an operational air quality modeling system can be used in situations when limited TRS emission information is available, in order to produce reasonably accurate forecast of plume position and its potential impact, of utility for preventing conflictive situations. The Methods section briefly describes the models employed and the methodology applied, the Results and Discussion section describes the results of the modeling, the plume layout in comparison with the location of the social complaint. Finally, we present the conclusions of the study.

METHODS

The present study simulates 11 events in which the local authorities received social complaints from the local population about the presence of malodorous substances in the area, with indication of date, hour and location of the event. The EPM officials went to the place for in situ verification and the procedure consisted of the perception or not of the odor, so that neither measurements nor air samples were taken. As a result of this procedure, the official report indicated whether or not the presence of the malodorous substance was verified. Table 1 presents the list of events with indication of date, time and location within the region depicted in “Fig. 1”.

The ARPS model, developed by the Center for Analysis and Prediction of Storms of University of Oklahoma, is an open source code based on the equations of fluid mechanics with a large eddy simulation approach for resolving mesoscale

Table 1. Date, time and location of the modeled events.

Date	Time	Location	Lat – Lon
Sep 10th, 2009	09:45–11:45	International Bridge	33°5'56.71"S, 58°14'54.73"W
Oct 12th, 2009	10:30–12:30	International Bridge	33°5'56.71"S, 58°14'54.73"W
Nov 3rd, 2009	22:00–02:20	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W
Nov 5th, 2009	08:00–10:00	Ñandubaysal Beach	33°4'5.80"S, 58°22'34.42"W
Nov 10th, 2009	14:00–20:00	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W
Nov 29th, 2009	21:00–22:30	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W
Nov 30th, 2009	10:30–10:50	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W
Nov 30th, 2009	14:30–21:30	International Bridge	33°5'56.71"S, 58°14'54.73"W
Dec 1st, 2009	21:30–23:45	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W
Dec 3rd, 2009	05:00–06:30	General Belgrano	33°1'18.64"S, 58°29' 8.63"W
Dec 15th, 2009	10:40–12:00	Gualeguaychú	33°0'26.66"S, 58°30'42.48"W

meteorological phenomena. The initial and boundary conditions required by ARPS are taken from the 3D outputs of BLM model, which runs operatively at the National Meteorological Service of Argentina. Aguirre *et al.* (2003, 2006) added to ARPS the algorithms that simulate the transport and dispersion of chemical species, and coupled it to a Lagrangian stochastic dispersion model. In a subsequent work, the validation of the code was made with results of wind tunnel experiments (Aguirre, 2005; Aguirre *et al.*, 2006). The input data required by ARPS includes: meteorological data (pressure, temperature and wind), surface data (vegetation type, normalized vegetation index and roughness), soil type, surface temperature and surface height above mean sea level. The surface data were obtained from a Landsat 5 satellite image of the National Institute for Space Research (INPE), Brazil, corresponding to November 19th, 2009, the closest date to the experiments with an available image. We use the satellite image processing soft IDRISI Taiga, developed by Clark University (www.clarklabs.org), to reduce the data to the resolution of 1 km adopted for the experiments. The cluster analysis of the energy spectrum bands allows identifying the different vegetation types, categorized according to the Olson World Ecosystem Classes (Olson *et al.*, 1985), as well as the corresponding surface roughness map. The Moderate Resolution Imaging Spectro-Radiometer Sensor (MODIS), mounted in TERRA satellite, is used to obtain the normalized vegetation index (NDVI), from images obtained from the Land Processes Distributed Active Archive Center (www.lpdaac.usgs.gov/get_data). The energy emitted by the earth surface elements in the thermal infrared bands, obtained from the Landsat 5 image, are converted to temperature values following the methodology proposed by Perez *et al.* (2003). The digital elevation model is obtained from the U.S. Geological Survey database (www.srtm.usgs.gov).

ARPS requires 3D meteorological fields of wind, temperature and pressure, with horizontal resolution of 1 km, as initial and boundary conditions. These data are provided by the operative BLM forecast of the National Meteorological Service of Argentina. BLM has been specifically developed for modelling low-level atmospheric circulations over coastal regions where the daily cycle of water-land thermal contrasts at the surface is the major driving mechanism for the atmosphere. We refer the reader to Berri *et al.* (2010) for the details about the BLM formulation. For the purpose of a brief description, it can be said that it is a hydrostatic model based on conservation equations of momentum; mass and heat, with a first-order turbulence closure. The horizontal domain of BLM is centered over the region depicted in "Fig. 1" and consists of 76 points in the latitudinal and longitudinal directions, with 1 km resolution. The vertical domain extends up to 2.5 km above the ground with 12 vertical levels log-linearly spaced. The simulations started always 1 hour before the moment of interest in order to allow for the model spin-up.

In order to validate the wind forecast, the modeled winds are compared to the observations from a meteorological tower operated by the National Meteorological Service under agreement with the Secretary of Environment and Sustainable Development of Argentina. The observed winds at 42 m are compared to the wind forecasts at the closest BLM level, i.e., 40 m. Since the observations are reported hourly, every event is validated from the previous to the following hour, so that the validation of the 11 events totalizes 46 hours. Since the wind direction observations are reported categorically in a 16-sector wind rose, i.e., N, NNE, NE, and so on; the wind direction forecast is converted to the corresponding category. The error in wind direction is calculated as the absolute difference between observed and modeled winds in such a way that 1 wind sector difference means a 22.5 degree error, 2 wind sectors mean a 45 degree error, and so on. In fact, the agreement of the modeled and observed wind sector means a potential error of 22.5 degrees, which is the uncertainty of the observation, so that in every calculation we added 22.5 degrees to the absolute difference. The wind speed observations are reported in m s^{-1}, so that in this case we calculate the root mean square error (rmse). Table 2 shows the average value of the errors of every event, although the 2 events of November 30th, 2009 are considered one, since the first event is very short (10:30 to 10:50) and the second one occurred shortly after (14:30 to 20:30). The average error of all events is 49 degrees for wind direction and 2.2 m s^{-1} for wind speed. The event of September 30th, 2009 has the largest error of 105 degrees, while in the other events the errors are not very far from the average value and some of them are only slightly above the uncertainty level of 22.5 degrees.

"Fig. 2" shows the scatterplot of forecast versus observed

Table 2. Average errors in wind direction (degrees) and wind speed (m s^{-1}).

Date	Wind direction absolute error (degrees)	Wind speed rmse (m s^{-1})
Sep 10th, 2009	105	2.3
Oct 12th, 2009	31	1.2
Nov 3rd, 2009	52	2.4
Nov 5th, 2009	22	2.2
Nov 10th, 2009	39	3.3
Nov 29th, 2009	52	1.4
Nov 30th, 2009	47	2.0
Dec 1st, 2009	72	0.8
Dec 3rd, 2009	29	2.9
Dec 15th, 2009	67	0.8

winds. The slope of the regression line indicates an overall good agreement in the case of wind direction, while in the case of wind speed it is clear that the model underestimates the observations. These characteristics of the wind errors will have more effect on the longitudinal extension of the plume than its geographical extension and span. Since the model underestimates the wind speed, the modeled plume will travel less far, but basically on the direction than the real one because there is no significant bias of the wind direction forecast.

The physical properties of the TRS point sources and emission rates are presented in Table 3.

The TRS emission from the wastewater treatment unit is considered at ground level, at ambient temperature and with zero exit velocity, because the Ecometrix report provides only the diameter of the tank of 46 meters (Tables A8.7-10 Ecometrix, 2006).

The substance known as TRS is actually composed of four other substances, namely, hydrogen sulfide (HS), methyl mercaptan (MM), dimethyl sulfide (DMS) and dimethyl disulfide (DMDS). The combination of these substances has a synergistic effect in the generation of unpleasant odors. In addition to that, each TRS component has a different detection threshold, according to Annex C of Ecometrix (2006), whose values are reproduced in Table 4.

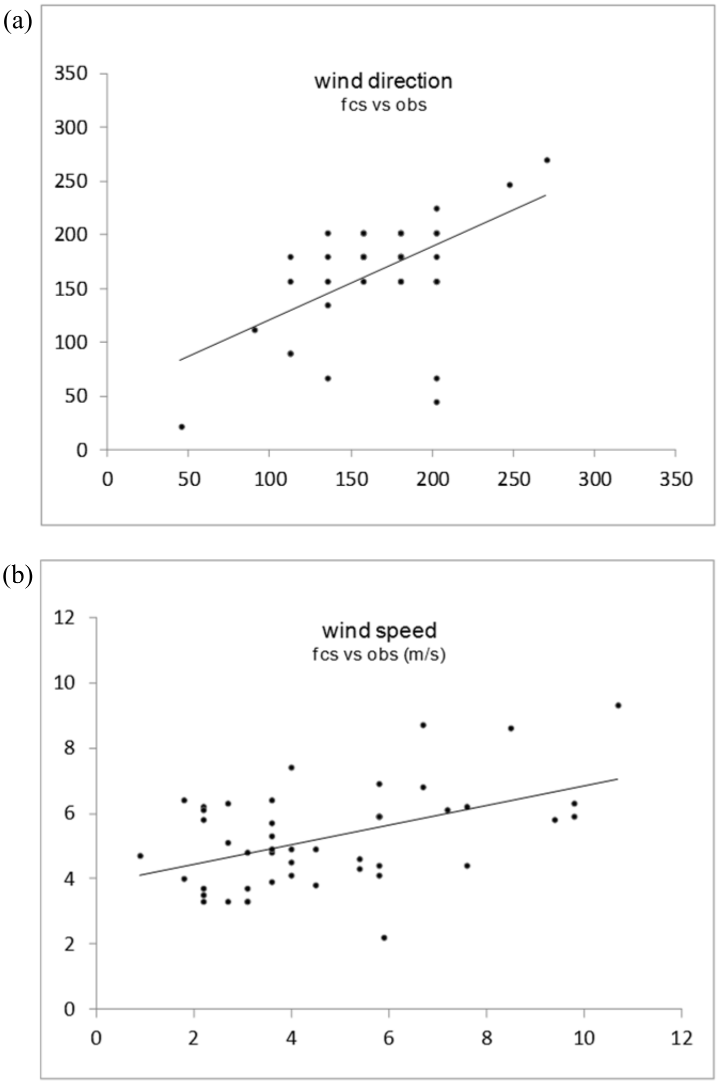


Fig. 2. Scatterplot of forecast versus observed (a) wind direction in degrees, and (b) wind speed in m s^{-1}.

Table 3. Physical properties of point sources and TRS emission rates, estimated as the annual average in normal operating conditions (based on information of Tables C2.1-1 and C2.3-1 of Ecometrix, 2006).

Source	Stack Height (m)	Stack Diameter (m)	Exit Velocity (m s^{-1})	Exit Temperature (°C)	Emission rate (g s^{-1})
Recovery boiler	120	4.6	22	160	4.73
Non condensable gases incinerator	120	4.6	22	160	0.49
Lime link	120	2.5	14	220	0.43
Wastewater treatment unit	0	see text for details	0	ambient	0.06

Table 4. Average detection thresholds in (μg m^{-3}), from Annex C of Ecometrix (2006).

Hydrogen Sulfide (HS)	Methyl Mercaptan (MM)	Dimethyl Sulfide (DMS)	Dimethyl Disulfide (DMDS)
0.7	2	3	23

Since ARPS does not identify a TRS component by its chemical composition because it can model a generic TRS substance; we applied the dispersion model to the totality of TRS. The simulation with ARPS is performed in the following way. The total mass of substance released by the source is represented, in all cases, by 500 particles emitted every 10 seconds, which are then dispersed in the atmosphere. The resulting TRS concentration is calculated at breathing level as the average value of the entire modeling period, in individual cells distributed all over the region. Each cell has a horizontal area of 300 m on each side and a height of 5 m, i.e., a total volume of 4.5 10^5 m^3. The mass of each particle is calculated in such a way that the total mass represented by the 500 particles equals the mass of substance released from the source during the 10-second period, which is the rate at which ARPS performs the calculations. Then, the number of particles contained in each cell is counted and this number is used to obtain the concentration C in μg m^{-3}, with the Eq. (1):

$$C = (n\ wp)/V \tag{1}$$

where n is the number of particles in the cell, wp is the mass of each particle in μg and V the volume of each cell in m^3. The mass of each particle is 0.1142 g, which results of dividing 57.1 g of substance emitted during a 10 second period, by the 500 particles (the mass of 57.1 g is equal to the sum of emission rates in g s^{-1} of the last column of Table 3, multiplied by 10 seconds). Considering the emission rate of each source from Table 3, the total emission of 500 particles every 10 seconds is distributed in the following way: recovery boiler 414 particles, non-condensable gases incinerator 43 particles, lime link 38 particles and wastewater treatment unit 5 particles.

The odor of a substance becomes noticeable when the concentration thereof exceeds a given value called detection threshold. For example, if $I = C/DT$ defines the detection index, with C the concentration and DT the detection threshold, then the substance becomes noticeable when $I \geq 1$. In air quality studies, the concept of synergistic effect states that the simultaneous presence of several malodorous substances makes the odors more noticeable. Therefore, we define a synergistic detection index I_s as:

$$I = \frac{CHS}{DTHS} + \frac{CMM}{DTMM} + \frac{CDMS}{DTDMS} + \frac{CDMDS}{DTDMDS} \tag{2}$$

where the numerator is the concentration of each TRS component and the denominator is the respective detection thresholds of Table 4. The concentration of each TRS component is calculated according to Eq. (1), with the physical parameters of Table 3 and percentage participation of Table 5. Since the information available on emission rates (Table 3) refers to the total TRS, we adopt the mixing ratios from Table C2.3-5, Annex C of Ecometrix (2006), which are reproduced in Table 5.

For example $CHS = 0.4033\ C$ (with C from Eq. (1)), since hydrogen sulfide contributes with a 40.33% (see Table 5) to total TRS. The synergistic effect can be easily understood with Eq. (2). For example, if individual concentrations were 1/4 of the respective detection threshold, each individual detection index would be 0.25 and then each substance would be unnoticeable. However, due to the synergistic effect, by adding up the four individual detection indices we obtain $I_s = 1$, which makes the TRS presence noticeable. The results of the numerical modeling, in terms of the spatial layout of modeled plumes and TRS concentrations, are compared with the geographical distribution of points in the area where the EMP officials received the social complaints of local population about the presence of malodorous substances.

RESULTS AND DISCUSSION

Table 6 summarizes the results of the eleven cases studied

Table 5. Percentage contribution to total TRS emission, according to Table C2.3-5, Annex C of Ecometrix (2006).

Compound	Percentage of TRS
Hydrogen Sulfide (HS)	40.33
Methyl Mercaptan (MM)	36.09
Dimethyl Sulfide (DMS)	14.49
Dimethyl Disulfide (DMDS)	9.09

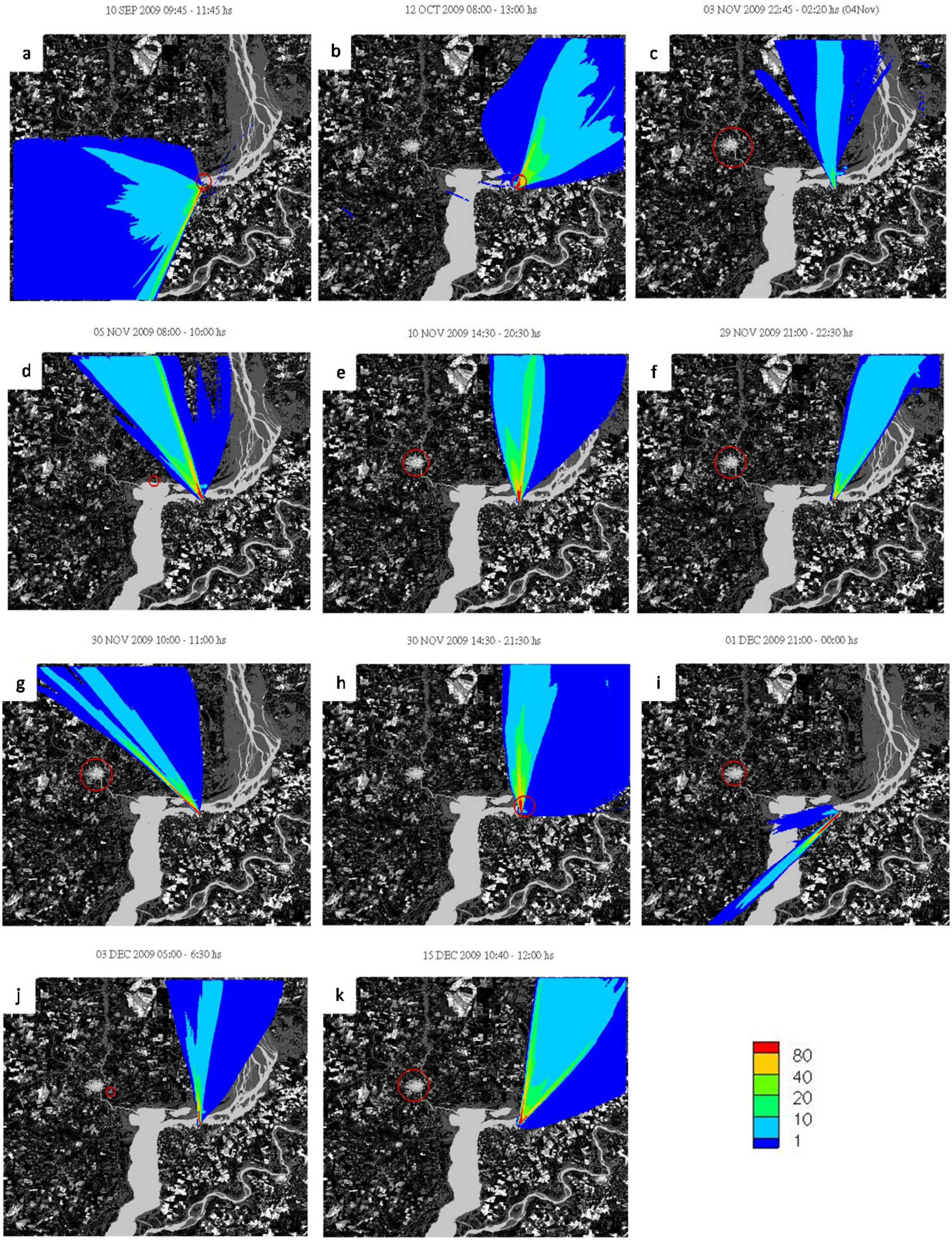
with indication of date, time and location of the social complaint; verification of malodor presence by EMP officials; and agreement or not of the position of the modeled TRS plume with the location of social complaint. In each of these events the EMP officials attended the scene for in situ verification.

A "yes" in the third column of Table 6 means that the EPM officials in fact verified the malodor presence, while a "no" means that the verification was negative. A "yes" ("no") in the fourth column of Table 6 means that the location of complaint is within (outside) the area cover by the modeled plume layout.

"Fig. 3" shows the TRS concentration in $\mu g\, m^{-3}$ corresponding to the 11 modeled cases of Table 6. As mentioned in the previous section, the simulations always started 1 hour before the period of the social complaint in order to allow for the model spin-up. "Fig. 3(a)" shows the plume for September 10th, 2009 when the social complaint was recorded in the International Bridge from 09:45 to 11:45, with a positive verification by EMP officials. The plume layout is predominantly to the West and Southwest, but the area of the International Bridge is not directly affected, only marginally. On October 12th, 2009, a social complaint was again recorded in the area of the International Bridge, from 10:30 to 12:30, with a positive verification by EMP officials. "Fig. 3(b)" shows the modeling result with a northeasterly plume, widely extended and directly affecting the location of the social complaint. On the night hours of November 3rd, 2009, several social complaints were recorded in Gualeguaychú, from 22:45 to 02:20 of the following day, which was negatively verified by EMP officials. In "Fig. 3(c)" it can be seen that the plume travels to the North, over an area quite distant from the location of the social complaint. "Fig 3(d)" presents the modeling result of November 5th, 2009, when the social complaint was recorded in the area of Ñandubaysal Beach from 08:00 to 10:00. The EMP officials reported a negative verification of the malodor presence, and the plume layout is such that it extends to the North and North-Northwest and therefore not impacting the location of the social complaint, although not far away from it. On November 10th, 2009, from 14:00 to 20:00 a social complaint was recorded in Gualeguaychú which had a negative verification by EMP officials. The result of modeling in "Fig. 3(e)" shows the plume extending to the North and North–Northeast, very far from the place where the social complaint was recorded. On November 29th, 2009 a social complaint was again recorded in Gualeguaychú, from 21:00 to 22:30, which had negative verification by EMP officials. The plume of "Fig. 3(f)" extends to the North–Northeast, very far away from the location of the social complaint. On November 30th, 2009 two simulations were performed to account for two social complaints on the same day but at different places. One of them was recorded from 10:30 to 10:50 in Gualeguaychú, and the other one, from 14:30 to 21:30, in the International Bridge; both negatively verified by the EMP officials. "Fig. 3(g)" shows the modeling result for the first complaint, in which we can see that the plume extends to the North and Northwest, i.e., to the North of Gualeguaychú. "Fig. 3(h)" corresponds to the second social complaint of that day, and

Table 6. Summary of modeled cases, with result of verification of complaints and agreement or not with plume position (see text for details).

Date and time	Location	EPM verification of malodor	Spatial agreement plume position/ complaint location	Fig. 2 panel
Sep 10th, 2009 09:45–11:45	International Bridge	yes	no	a
Oct 12th, 2009 10:30–12:30	International Bridge	yes	yes	b
Nov 3rd, 2009 22:00–02:20	Gualeguaychú	no	no	c
Nov 5th, 2009 08:00–10:00	Ñandubaysal Beach	no	no	d
Nov 10th, 2009 14:00–20:00	Gualeguaychú	no	no	e
Nov 29th, 2009 21:00–22:30	Gualeguaychú	no	no	f
Nov 30th, 2009 10:30–10:50	Gualeguaychú	no	no	g
Nov 30th, 2009 14:30–21:30	International Bridge	no	yes	h
Dec 1st, 2009 21:30–23:45	Gualeguaychú	no	no	i
Dec 3rd, 2009 05:00–06:30	General Belgrano	no	no	j
Dec 15th, 2009 10:40–12:00	Gualeguaychú	no	no	k


10 SEP 2009 09:45 - 11:45 hs

12 OCT 2009 08:00 - 13:00 hs

03 NOV 2009 22:45 - 02:20 hs (04Nov)

05 NOV 2009 08:00 - 10:00 hs

10 NOV 2009 14:30 - 20:30 hs

29 NOV 2009 21:00 - 22:30 hs

30 NOV 2009 10:00 - 11:00 hs

30 NOV 2009 14:30 - 21:30 hs

01 DEC 2009 21:00 - 00:00 hs

03 DEC 2009 05:00 - 6:30 hs

15 DEC 2009 10:40 - 12:00 hs

Fig. 3. TRS concentration in μg m^{-3}, corresponding to the 11 modeled cases of Table IV. The hours indicate the modeling period.

we can see that the plume is traveling to the North and North–Northeast, in fact extending over the International Bridge where the social complaint was recorded. On December 1st, 2009, from 21:30 to 23:45, a social complaint was recorded in Gualeguaychú, which had a negative verification by EMP officials. As we can appreciate in “Fig. 3(i)”, the plume is directed towards the Southwest displaying a very narrow layout and quite far away from Gualeguaychú. On December 3rd, 2009 the social complaint in General Belgrano, from 05:00 to 06:30, had a negative verification by EMP officials. The plume layout of “Fig. 3(j)” extends northward and away from the location of the social complaint. Finally, a similar situation took place on December 15th, 2009 with the social complaint recorded in Gualeguaychú, from 10:40 to 12:00. The EMP officials did not verify the presence of malodors, and the plume layout of “Fig. 3(k)” shows a northeasterly orientation over an area very far away from Gualeguaychú.

We calculated the synergistic detection index I_s for the event of October 12th, 2009 that was the only case in which the position of the modeled plume agreed with the location of the social complaint, which was verified by EMP officials. “Fig. 4” presents the concentration in µg m^{-3} of each TRS component, namely dimethyl sulfide “Fig. 4(a)”, dimethyl disulfide “Fig. 4(b)”, methyl mercaptan “Fig. 4(c)”, and hydrogen sulfide “Fig. 4(d)”. The last panel, “Fig. 4(e)”,

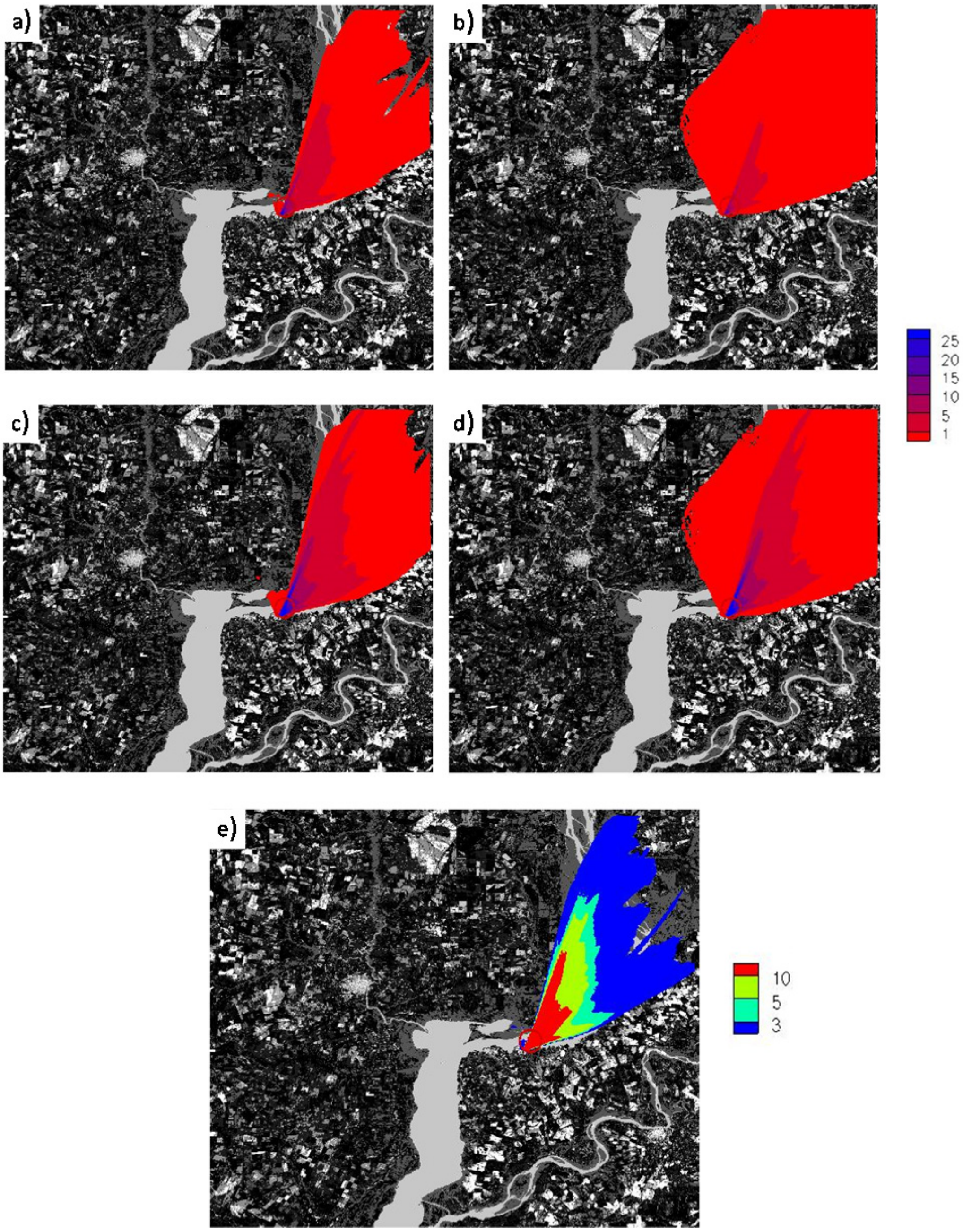


Fig. 4. Concentration in µg m^{-3} of: a) dimethyl sulfide; b) dimethyl disulfide; c) methyl mercaptan; d) hydrogen sulfide, and e) synergistic detection index I_s (see text for details), corresponding to the event of October 12th, 2009.

Table 7. Distribution of number of cases according to plume position, social complaint location and in situ verification of malodor presence (see text for details).

		Spatial agreement plume position/complaint location	
		yes	no
EPM	yes	1	1
verification	no	1	8

presents the synergistic detection index I_s calculated according to Eq. (2) and using the detection thresholds of Table 4. As it was already indicated, ARPS does not identify individual TRS components, so that each one was modeled separately as a generic TRS substance. As a consequence of the synergistic effect, the detection index over the area of the International Bridge is between 3 and 5, a level that makes the odor not only clearly recognizable but also even annoying for most sensible persons.

From the point of view of model validation, the successful modeling cases are those in the main diagonal of Table 7, i.e., a positive (negative) in situ verification coincides with a plume position over (far from) the site. They amount 9 out of 11 events which represents a significant percentage of successful modeling cases. Eight of the successful modeling cases (lower right box of Table 7), are those in which the negative verification of the malodor presence matched with a plume position far from the site. The remaining successful case corresponds to the event of October 12th, 2009 (upper left box of Table 7). In this case the modeling result "Fig. 4" shows a plume located over the site, with a synergistic detection index well over the threshold value of 1 that makes the odor not only recognizable but also annoying. In one of the two unsuccessful modeling cases (September 10th, 2009, upper right box of Table 7), the plume is marginally distant from the site of the social complaint. This disagreement could be justified by the fact that the error of 105 degrees in wind direction of this event is the largest one of all them. Finally, the other unsuccessful case corresponds to November 30th, 2009 in which the modeled plume is located over the region of the social complaint, but the situation was negatively verified by EMP officials. The reason for the disagreement could be due to the wind direction changes during the event. This was the longest modeled case that lasted for 7 hours and the plume was meandering during that time; first from SSW to the S, then back to the SSW, and finally to the S and SSE.

CONCLUSIONS

The validation of modeled winds with the observations from a meteorological tower indicates reasonably accurate wind forecasts. The simulation of the malodorous events provided very good results since 9 of the 11 studied events are successful modeling cases. Despite the inherent uncertainty of numerical simulations, the implemented modeling system is able to produce forecasts of plume position and potential impact with acceptable accuracy. The conclusion of the study is that the adopted methodology can be of utility not only in diagnostic studies but also for preventing conflictive situations.

ACKNOWLEDGEMENT

The authors thank the National Meteorological Service of Argentina for facilitating the wind data of the meteorological tower.

This work is part of the PhD thesis of Emiliana Orcellet in Science and Technology (version Chemistry), at the National University of San Martín, Argentina. This study was supported by research grant PICT2008-1417, and partially by research grant PICT2012-1667, from the National Agency for Scientific and Technological Promotion (ANPCyT) of Argentina.

REFERENCES

Aguirre, C.A., Simoëns, S. and Ayrault, M. (2003). Chemically Reactive Dispersion into Atmospheric Boundary Layer. International Workshop on Physical Modeling of Flow and Dispersion Phenomena. Proceeding of PHYSMOD 2003, Prato, Italy, pp. 154–158.

Aguirre, C. (2005). *Dispersión et Mélange Atmosphérique Euléro-lagrangien de Particules Fluides Réactives*, Thèse de doctorat. Université Claude Bernard Lyon 1, France, 115-2005, 1-323, 2005.

Aguirre, C., Brizuela, A., Vinkovic, I. and Simoëns, S. (2006). A subgrid lagrangian stochastic model for turbulent passive and reactive scalar dispersion. *Int. J. Heat Fluid Flow* 27: 627–635.

Berri, G., Sraibman, L., Tanco, R. and Bertossa, G. (2010). Low-level wind field climatology over the La Plata River region obtained with a mesoscale atmospheric boundary layer model forced with local weather observations. *J. Appl. Meteorol. Clim.* 49: 1293–1305.

Berri, G., Galli Nuin, J., Sraibman, L. and Bertossa, G. (2012). Verification of a synthesized method for the calculation of low-level climatological wind fields using a mesoscale boundary-layer model. *Boundary Layer Meteorol.* 142: 329–337.

Ecometrix (2006). Estudio de Impacto Acumulativo Plantas de Celulosa en Uruguay – Anexo C Evaluación de la Calidad de Aire. http://www.offnews.info/downloads/Uruguay_CIS_AnnexC_Oct2006.pdf.

U.S. Environmental Protection Agency (EPA) (1990). Reference Guide to Odor Thresholds for Hazardous Air Pollutants Listed in the Clean Air Act Amendments. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=40610#Download.

Olson, J., Watts, J. and Allison, L. (1985). *Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database.* CDIC, Oak Ridge, NDP-017, Tennessee.

Pérez, A, Calle, A. and Casanova, J. (2003). Cálculo de la Temperatura Superficial a partir de Datos Landsat TM. 10° Congreso AET. Cáceres, España, pp. 95–98.

Xue, M., Droegemeier, K. and Wong, V. (2000). The Advanced Regional Prediction System (ARPS). A multi-scale nonhydrostatic atmospheric simulation and prediction model. Part I: Model dynamics and verification. *Meteorol. Atmos. Phys*. 75: 161–193.

Xue, M., Droegemeier, K., Wong, V., Shapiro, A., Brewster, K., Carr, F., Weber, D., Lin, Y. and Wang, D. (2001). The Advanced Regional Prediction System (ARPS). A Multi-scale nonhydrostatic atmospheric simulation and prediction model. Part II: model physics and applications. *Meteorol. Atmos. Phys.* 76: 143–165.

Received for review, March 11, 2015
Revised, August 14, 2015
Accepted, October 20, 2015