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USING SIMULATED TORNADO SURFACE MARKS TO HELP DECIPHER NEAR-GROUND WIND FIELDS

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1 INTRODUCTION

Numerical simulations of tornadoes show a rich complexity near the surface. The highest radial, azimuthal and sometimes vertical wind speeds generally occur within the lowest tens of meters above the ground. The tornado's structure and intensity proves to be strongly sensitive to properties of the near-surface inflow and can change rapidly in time for some conditions. In addition, transient effects, asymmetry of the main vortex, and interaction with large mass loading of debris, have all proved to be critical complications in some regimes. Studying these effects in the field is problematic because mobile Doppler radar, which provides the best tornado wind field measurements, cannot probe below about 20 m above ground. Moreover, deducing complete wind fields from single Doppler data generally requires assumptions about tornado symmetry, steadiness, and correlation between scatterer and air velocities that are more uncertain near the surface.

There is, however, a direct signature of the low-level wind field that is sometimes available: the "surface marks" or "debris tracks" left behind by the tornado. We have in mind here patterns left behind when a tornado traverses a relatively uniform surface such as a plowed field, rather than destruction of individual structures such as buildings or trees. The latter has been heavily studied and can provide critical information about tornado strength; however, coverage of structures is generally sparse and their interaction with the wind field complex. Ground marks provide complementary information that, when available, may give a more complete and decipherable record.

A handful of studies decades ago attempted to discern tornado wind speeds and structure from ground marks (e.g., Fujita et al. (1967, 1970, 1976); Fujita (1981); Davies-Jones et al. (1977)). Difficulties in interpreting the marks limited the utility of these efforts, and little scientific attention has been paid to them since. In the present work we revisit this field using large-eddy simulations (LES) of tornadoes with interacting debris, including an accounting on the surface of where soil is removed or deposited, to produce simulated tornado tracks together with the complete wind fields and debris clouds responsible for generating them. This allows the origins of particular marks to be determined in given cases. We hope that this knowledge, perhaps taken together with concurrent Doppler observations, may allow some detailed information about time dependent tornado wind fields near the surface to be determined from field observations of surface marks. As a byproduct we can also reassess interpretations of tornado surface marks that appear in the older literature.

2 LES MODEL AND SIMULATIONS

As part of a longstanding effort to better understand the near-surface intensification of tornadoes, we have been conducting a series of simulations exploring the effects of vortex asymmetry (particularly due to translation), transient evolution and debris loading. It is examples from this simulation set that are put to use for the present study. The high-resolution LES model and simulation procedures are ones we have used extensively in previous work (e.g., Lewellen et al. (2008) and references therein). Multiple debris species can be included, each treated in the simulation as additional pressureless "fluids" of variable density, interacting with the airflow through drag forces. For the present work we have added detailed surface accounting of debris that is removed and deposited as the tornado translates along the surface, producing an effective surface debris track. For comparison we also collect simulated ground traces of wind field variables such as peak wind speeds or pressure drops encountered at each surface point, and sometimes orientable wind signatures (such as might be produced by idealized "corn stubble" attached to the surface).

The primary simulations we sample here were performed with finest vertical grid spacing of 1 m at the surface, 4 or 5 m finest horizontal resolution in the central corner flow, simulation domains of dimensions 2 km laterally and 2-3 km vertically. Simulated times of hundreds of seconds produced simulated tracks from a few

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to several kilometers in length depending on tornado translation velocity. The simulations include quasi-steady translating tornadoes with different corner flow swirl ratios, as well as evolving tornadoes strengthened through the process of "corner flow collapse" (Lewellen and Lewellen, 2007a,b). Translation velocities over the surface were varied between 5 and 25 m s^{-1}. Most simulations were performed with a single debris species, a nominal coarse "sand" comprised of spheres of diameter d = 1 mm and density ratio relative to air of σ/ρ = 2000. In some simulations up to three debris species were included simultaneously. To good approximation the debris aerodynamics in the tornado corner flow is dependent on σ and d only through the combination σd (Lewellen et al., 2008), so the "coarse sand" results are also relevant to much larger debris of much lower density (e.g., short lengths of dried cornstalk). There is considerable uncertainty in the parameterization of the debris pickup off the surface, much of it reflecting real physical variability in conditions (e.g., soil moisture content, debris shape, presence of vegetation, debris availability, etc.). We have varied surface parameters as tests of sensitivity but have not attempted to correlate any particular choices with specific natural surfaces.

3 RESULTS

Figures 1-8 show sample simulation results for different conditions indicated in the figure captions. We focus on the appearance of the surface tracks here, but for reference the peak removal and deposition levels in the figures represent sand layer depths of order a few centimeters. Figure 1 provides tracks from four "corner flow collapse" cases. The corner flow collapse driving the near-surface vortex intensification is triggered purely by perturbing the low-level inflow over a single quadrant of the outer domain boundary. The cases differ in the choice of quadrant; the symmetry between the choices is broken by the slow translation velocity of the parent vortex. Dramatic changes in the magnitude, onset and duration of the vortex intensification and structure and motion of the near-surface vortex result, accompanied by dramatic changes in the surface markings. The figure illustrates both the sensitivity of tornado evolution to changes and asymmetries in the near-surface layer and the complexity and variability of the surface tracks that result.

Figures 2 and 3 show sample results from quasi-steady translating tornado simulations. The first would be categorized as a "medium swirl" tornado, the second as "high swirl". In addition to the track of net sand removal/deposition, the figures include tracks of peak pressure drop over a given surface point, and peak horizontal wind speed (relative to the ground) at 0.5 m height. At a sample instant in time cross-sections are also given for the variables that, as they evolve in time and sweep over the surface, ultimately produce the corresponding surface tracks: surface pressure drop, wind speed at 0.5 m height, and debris flux at the surface. Figures 4,5 show track variation for sample medium and high swirl tornadoes as a function of translation speed. Figures 6,7 provide additional surface tracks for the cases in figures 2 and 3 to help interpret the origins of different surface marks, and figure 8 samples results from two idealized simulation cases designed for the same purpose.

In assessing the utility of the simulations it is important to consider the robustness and reproducibility of the appearance of the surface marks. Simulations were performed with the horizontal resolution coarsened by a factor of two, producing tracks that were essentially similar to their fine grid counterparts other than some lost details. Simulations with multiple debris species allowed comparison of tracks produced by different size debris within the same tornado; tracks of 0.5, 1, and 2 mm sand were found to be very similar. Changes in surface pickup parameters generally led to modest changes in surface track appearance, though dramatic changes in the former can also lead to dramatic changes in the latter (e.g., compare figures 3e, 5b and 8c).

As with their real counterparts, the simulated tornado tracks show a wealth of widely varying ground marks. Their interpretation is complicated because they are produced by a convolution of events in time and space, for example patches of removal toward the front of the tornado being overrun subsequently by patches of deposition. An advantage of simulated tracks is that the entire time history of the field variables responsible for them can be made available for analysis, if necessary, to determine the origins of different types of marks. We have in some cases compared time animations of the debris flux at the surface with the subsequent debris track to effectively "watch" the stripping away and laying down of soil. We have also collected separate component tracks of removal alone and deposition alone (e.g., figures 6 and 7), and have performed auxiliary simulations including: ones with multiple debris species differing only by where they originated on the surface; ones where the surface source was shut off thereby producing a track of debris deposition with lofted debris falling out later than debris that never leaves the near-surface layer (e.g., figures 6d and 7d); and ones where a track was collected artificially from a non-translating (and therefore axisymmetric in the mean) tornado as if it were moving with a specified translation speed (e.g., figure 8a,b).

4 INTERPRETING AND ANALYZING TORNADO SURFACE MARKS

There is a radial inflow along the surface that accelerates both radially and azimuthally as it approaches the tornado center, before turning rapidly upward in the tornado corner flow. Driven by this flow, debris is initially carried along the surface in a shallow layer, with some fraction unable to follow the upward turning air in the corner flow and the remainder lofted upward (tens or hundreds of meters) and centrifuged outward before dropping back to the surface. Accordingly the debris flux (e.g., figures 2f, 3f, 8b, 8d) has five identifiable components: deposition and removal in the inflow layer, deposition and removal in the interior corner flow, and deposition of fully lofted debris. Each is responsible for different features of the debris tracks produced, with their relative weights depending on tornado type, debris properties, etc.. The first two deposition categories are correlated with regions of strong horizontal convergence; the removal is correlated with regions of larger turbulent kinetic energy. Asymmetries in the near-surface flow, such as those from the vortex translation, play a critical role in the appearance of the simulated tracks. Considering the near-surface flow in a translating tornado to be a superposition of an axisymmetric flow field and a translation velocity (as is frequently done) is often not a very good approximation (e.g., compare figures 2e and 8a).

In general, we have found that the origin of even some very pronounced marks can involve the interaction of several factors and therefore change significantly and in complicated fashion as cases are varied. Finer-scale alternating deposition and removal marks away from the central region are typically traceable to patterns of inflow rolls in the surface layer. The strongest central deposits are from debris left behind when flow turns sharply upward in the corner region (typically in a loose annulus or arc). More extensive swaths of deposition away from the center are typically from lofted debris. The relative importance of the lofted deposits to the central corner flow deposits increases with decreases in swirl ratio or debris σd. The addition of translation to a cyclonic vortex has several effects. In the far-field it can lead to more removal on the right of the tornado path where the swirl and translation velocities add. But it also tends to tilt the vortex (typically right and rearward near the surface relative to the vortex center aloft) which can lead to greater removal to the left and front in the near field. The accompanying tilt of the debris cloud leads to asymmetric deposits of lofted debris, typically right and rearward. Translation also affects the appearance of the central deposition by making the corner flow updraft just off the surface less symmetric.

Features such as “cycloidal” and “drift” marks, “lineation” and “scalloping”, commonly identified in surface tracks of real tornadoes by Fujita and his colleagues 30-40 years ago are often prominent in the simulated tracks. Many aspects of their interpretations of the origins of these features are supported by the simulation results, but others are not. Most significantly, the appearance of well defined lines of deposition were almost invariably interpreted as the results of the central convergence of a vortex or vortices traveling along the surface, either the main tornado vortex (producing “lineal” marks) or secondary “suction” vortices rotating about the tornado (producing cycloidal marks or scalloping). In the simulations, deposition tracks sometimes coincide with the main vortex path, but often well-defined straight tracks of debris arise from the deposition of lofted debris (e.g., the swaths to the right of the central vortex transit in figures 4a,b) or from surface convergence regions away from the vortex center (e.g., in figure 1). Perhaps even more surprising, while we generally find prominent cycloidal lines of deposition in simulated tracks of high-swirl tornadoes with multiple vortices (e.g., figures 3, 5) we do not generally find that they coincide with the tracks of the secondary vortices (e.g., figure 3c,d vs. figure 3e,f). Moreover, we sometimes find cycloidal lines where there is only a single vortex at the surface with an essentially straight path (e.g., figure 4a, or figure 1g,h where the cycloids in the track are seen to arise before the breakup into secondary vortices seen in the pressure track). The cycloids in the simulations arise from debris deposited beneath the central annular updraft that has converged from a much larger area, picking up local fluctuations in debris amount from turbulent flow structures encountered along the way (e.g., inflow rolls); the region of convergence around secondary vortices (and hence their ability to organize significant populations of debris) is much smaller. That cycloidal deposition marks don’t necessarily coincide with “suction” vortex paths affects other interpretations as well. For example Fujita et al. (1976) infer that “scalloping” arises when the speed of traverse of the secondary vortices around the tornado is slow, while faster traverse leads to “looping”; the simulations of figures 3 and 8c suggests that a transition from scalloping to looping may just indicate an increase in debris availability at the surface, rather than a change in secondary vortex behavior.

What can be learned more quantitatively from surface tracks? An important quantity that generally can be deduced is the radius of the updraft annulus at the surface; if this is determined for a real tornado for which Doppler measurements of core size aloft are available it would provide critical information about the level of near-surface intensification within that tornado. It may be possible to deduce the ratio of radial to swirling flow in the inflow layer by studying the tracks from surface inflow rolls and knowing the translation velocity. We are also exploring the utility of different statistical measures for analyzing surface tracks including different averages, power spectra and autocorrelation functions. While Fujita's original method of computing the ratio of rotation velocity to translation velocity from cycloidal marks is called into question by our findings, a usable substitute is still a possibility.

5 CONCLUDING REMARKS

Surface tracks from simulated tornadoes differing in corner flow structure, translation velocity, transient behavior and debris and surface properties show a wide variety of structures . Surface tracks represent a convolution in time and space of overlapping removal and deposition of debris. This produces a complex and not easily decipherable signature, but one that contains a great deal of information about two critical regions of the tornado flow that are not easily measured: the near-surface and corner flow.

While at this point we can look in detail within a given simulation to determine the origin of the particular ground markings in that case we are still far from a translation dictionary systematically deciphering the meaning of surface marks in the more general case. A critical issue is the extent to which a set of tornado surface marks are unique to the tornado and environment that generated them. If there is a high degree of uniqueness then it would seem worth trying to understand what creates the signatures in detail, as it may provide a wealth of useful information complementary to Doppler retrievals and individual surface probes. On the other hand if quite different tornadoes can produce similar tracks (e.g., if some properties of the surface or debris are varied appropriately) then the potential utility is reduced, with a successful deciphering of the track perhaps requiring information about the surface or conditions that are not readily available.

We would argue that the prospects are encouraging enough to warrant documentation of surface markings when available, particularly for cases where useful Doppler measurements have been gathered. As Fujita pointed out, this often requires aerial photography from a relatively low angle, otherwise there is often not enough contrast to make modest deposition or removal of debris visually apparent. Photography from a UAV might be a simple and cost effective option.

6 ACKNOWLEDGMENTS

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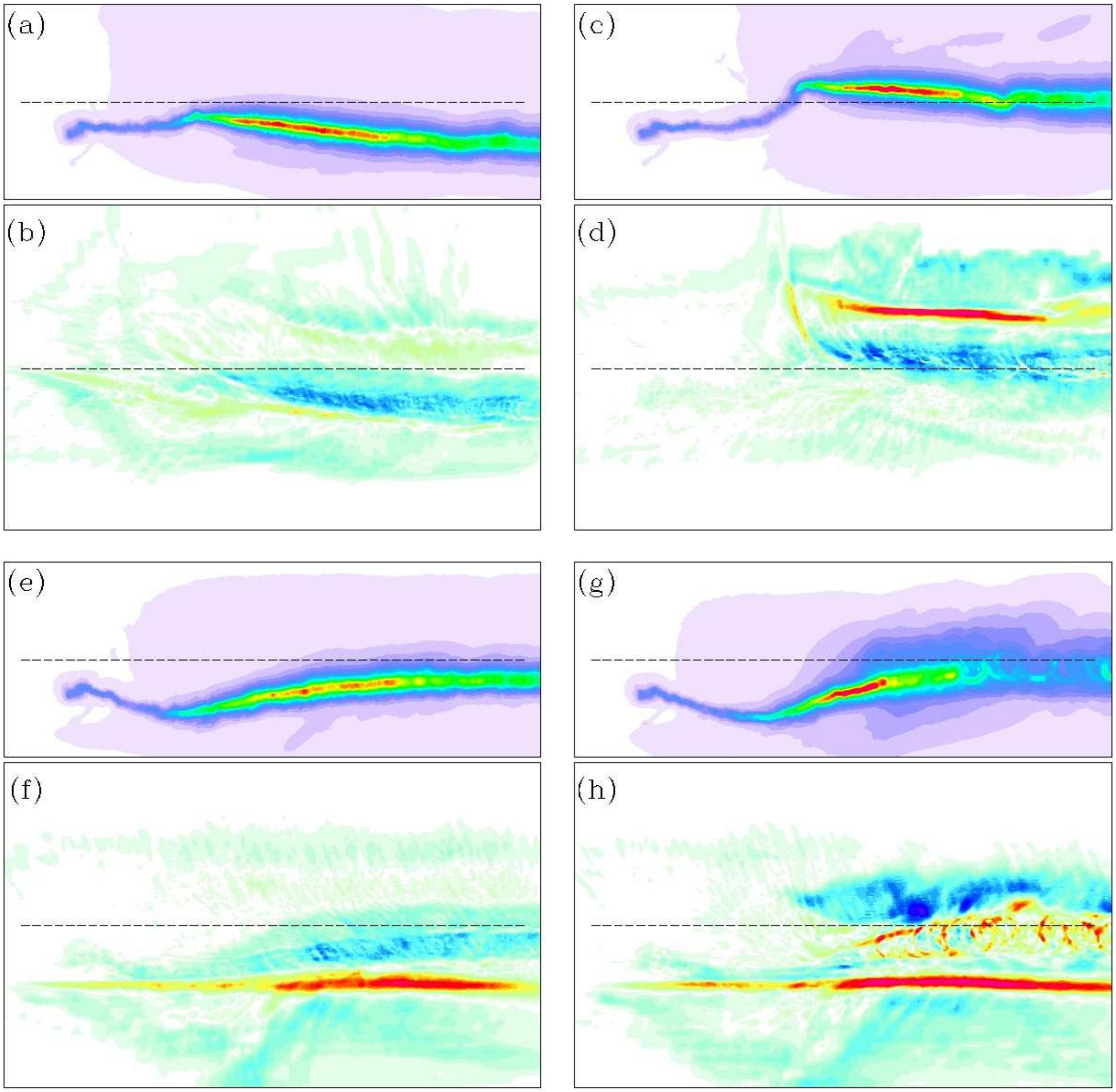

Figure 1: Surface tracks from four simulated corner flow collapse tornado evolutions showing peak pressure drops encountered at the surface (panels a,c,e,g) and net removal/deposition of 1 mm "sand" (panels b,d,f,h with blue indicating heavy removal, red indicating heavy deposition). In each case the large-scale vortex aloft is translating from left to right (west to east) at 5 m/s with the corner flow collapse triggered by impeding one quadrant of the low-swirl near-surface inflow: the northwest quadrant for panels a,b; NE for c,d; SW for e,f; and SE for g,h. The panel domain lengths are 1.65 km and the dashed lines indicate the track of the center of the large-scale vortex aloft.

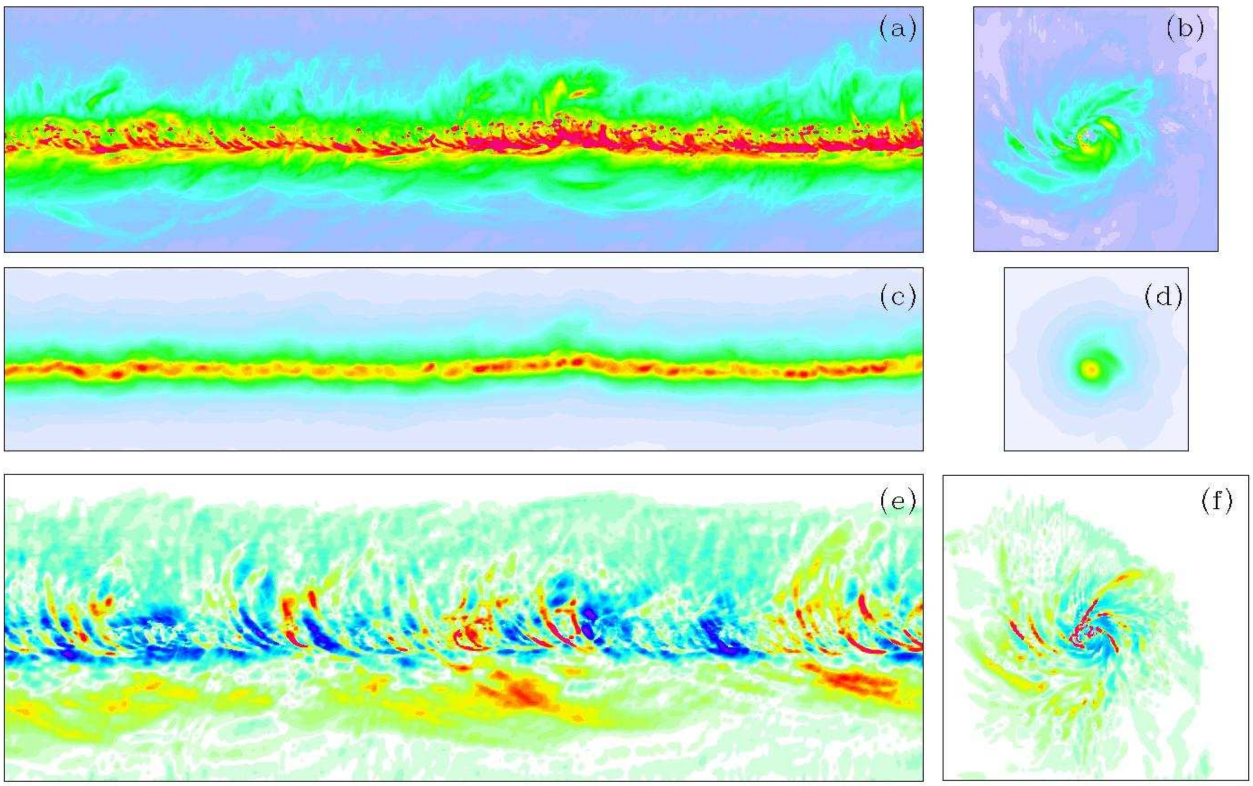

Figure 2: 3 km long surface tracks from a simulated quasi-steady "medium-swirl" tornado translating at 15 m/s over 1 mm "sand". Panel (a) shows peak horizontal velocities encountered 0.5 m above each surface point; (b) gives an example of the horizontal velocity field at 0.5 m height at one instant in time; (c) shows peak pressure drops encountered at the surface; (d) a sample surface pressure field at one instant; (e) shows net removal/deposition of sand (with blue indicating heavy removal, red indicating heavy deposition); and (f) a sample field of instantaneous vertical debris flux off the surface (reds indicating deposition, blues removal).

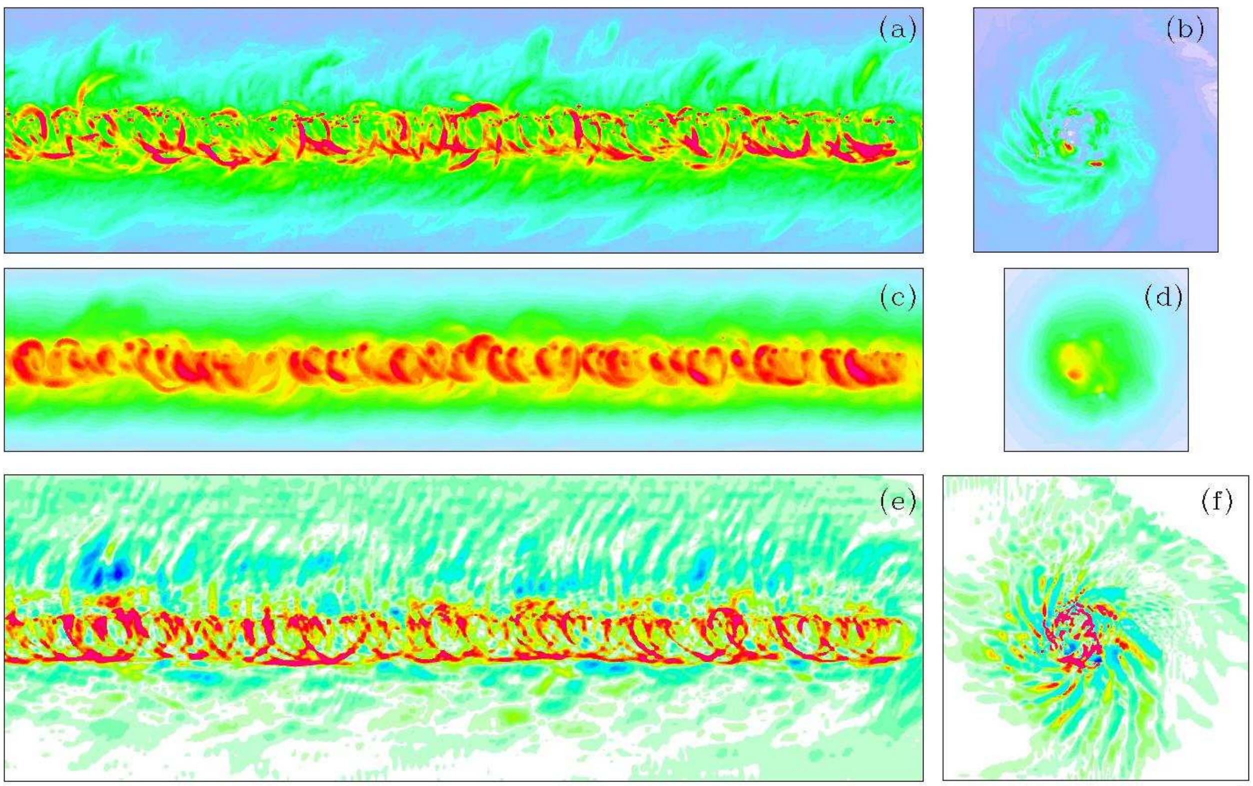

Figure 3: As in figure 2 but for a simulated "high-swirl" tornado.

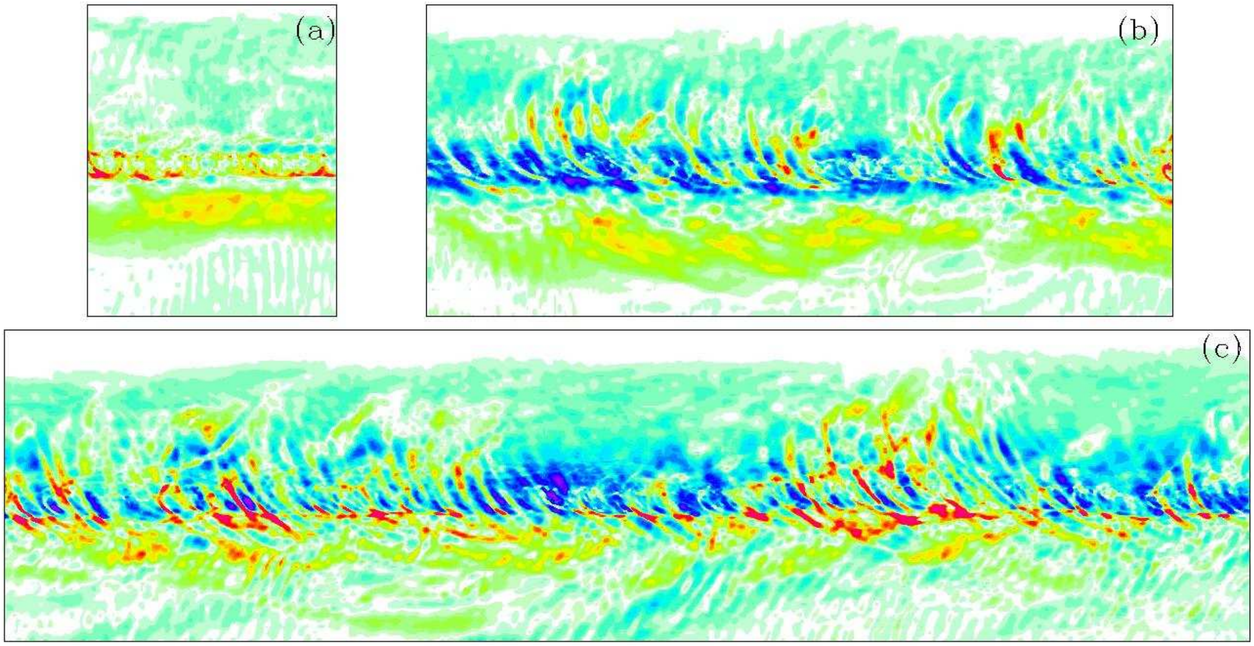

Figure 4: Debris deposition/removal tracks of simulated quasi-steady “medium-swirl” tornadoes translating at (a) 5 m/s, (b) 15 m/s, and (c) 25 m/s. The domains in each case represent 160 s of tornado evolution. The color scale has been scaled between figures according to the time the tornado spends over the surface (e.g., the same red shade in (a) indicates 3 times as much deposition as in (b) and 5 times as much as in (c)). Case (b) is the same as in figure 2.

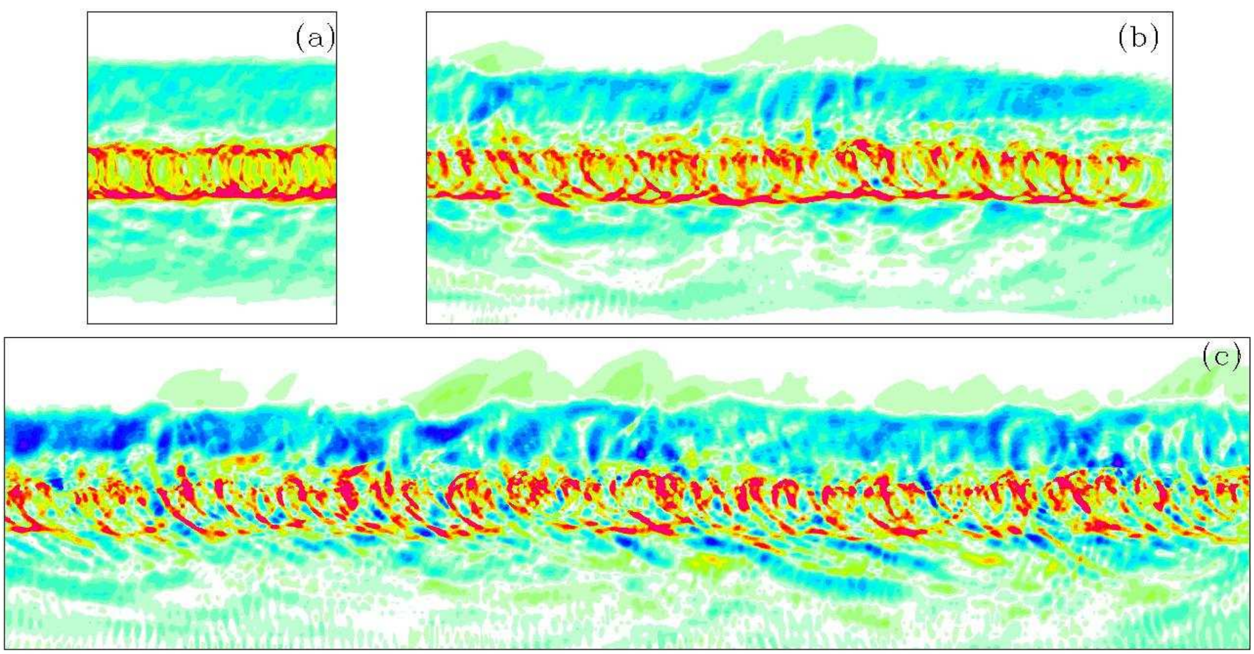

Figure 5: As in figure 4 but for simulated “high-swirl” tornadoes. These simulations also use a different set of surface “pick up” parameters than those in figures 2-4.

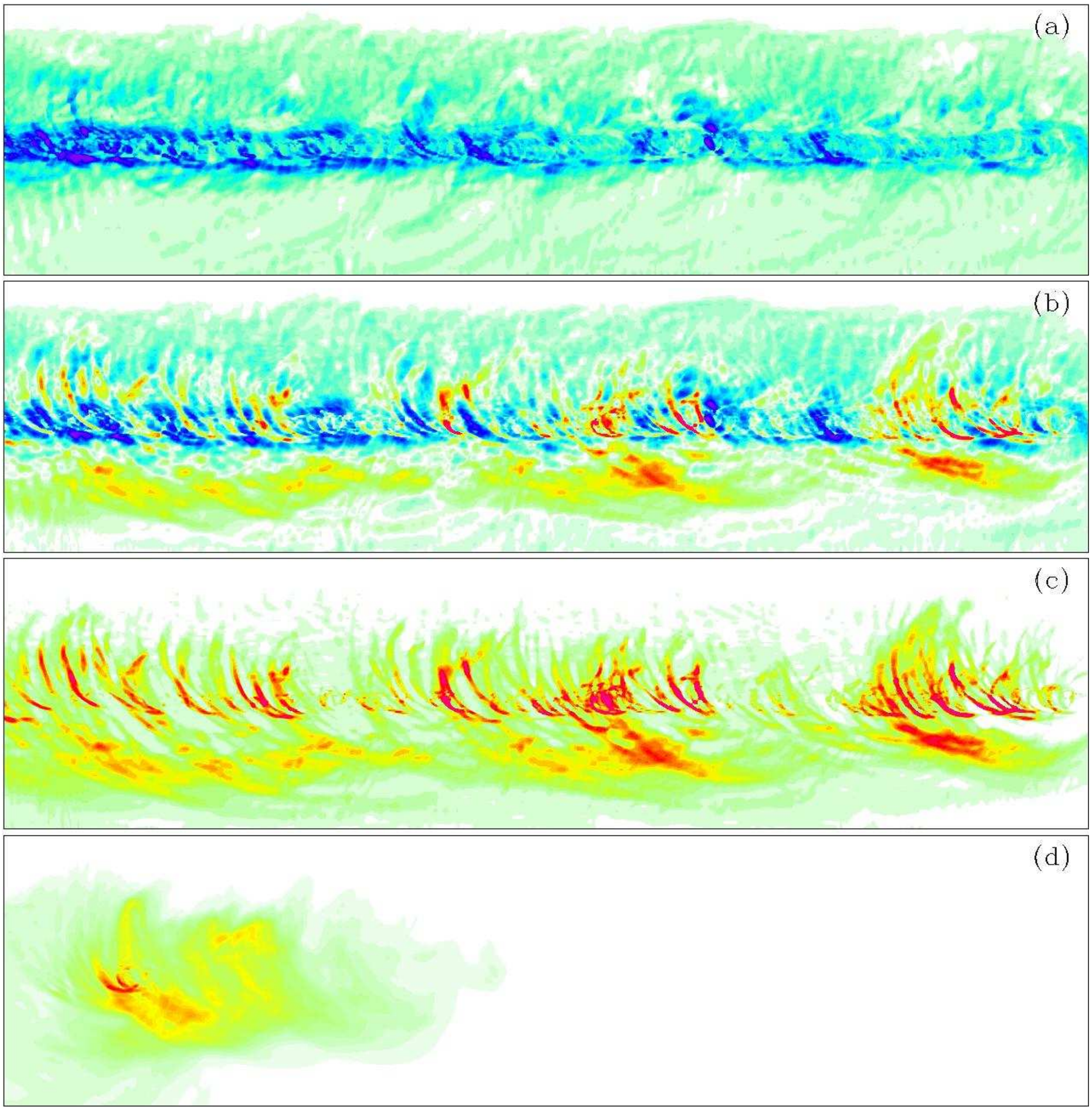

Figure 6: Additional 4 km long tracks from the medium-swirl case of figure 2. Panel (b) repeats the deposition/removal track (as in figure 2e); (a) shows removal alone; (c) deposition alone; and (d) the deposition track produced in this case when the surface source is abruptly shut off.

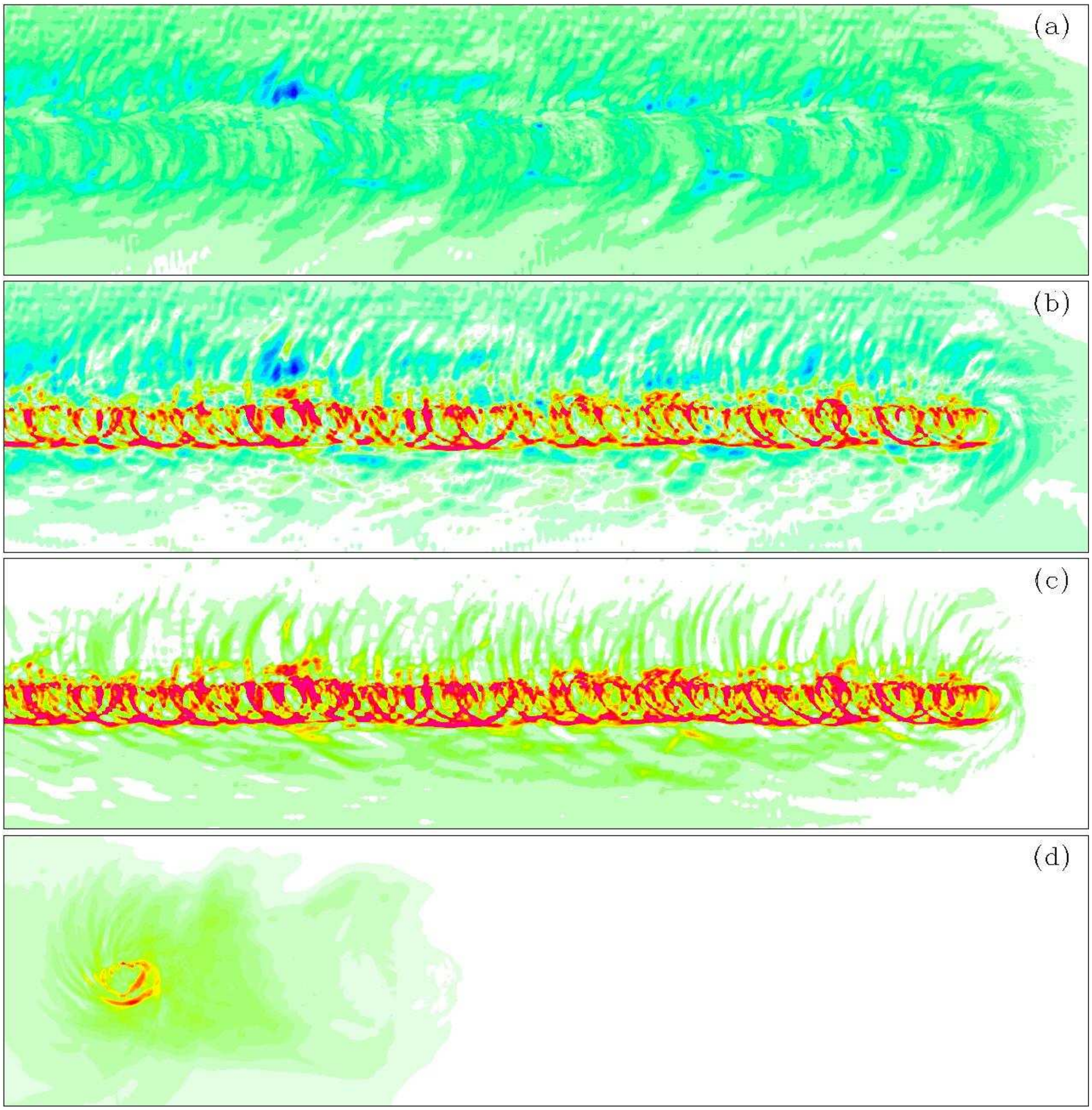

Figure 7: As in figure 6 but for the high-swirl case of figure 3.

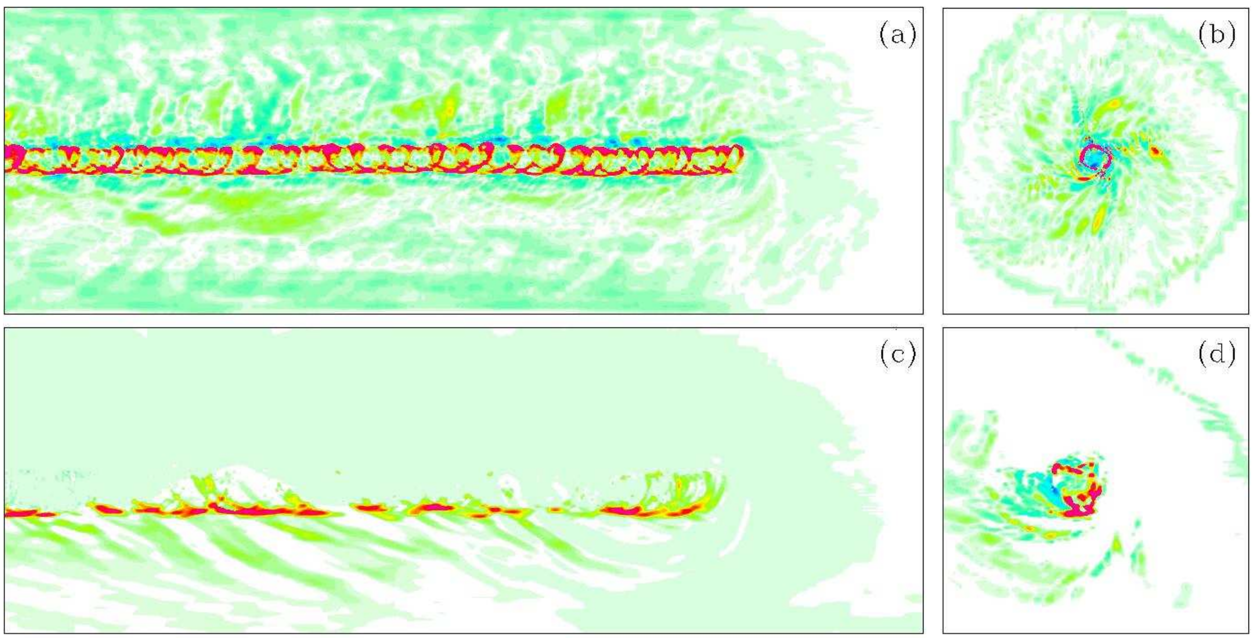

Figure 8: Surface deposition/removal tracks (panels a,c) and sample instantaneous vertical debris fluxes at the surface (b,d) for two idealized simulation cases. In (a,b) a surface track is artificially collected from a non-translating (and therefore axisymmetric in the mean) tornado as if it were moving at 15 m/s; otherwise this case can be directly compared with that in figure 2. The simulation of (c,d) is directly equivalent to that of figure 3 except only a very thin layer of sand (1 kg/m^2) has been made available at the surface for removal.