A New Pathway for Tornadogenesis Exposed by Numerical Simulations of Supercells in Turbulent Environments

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(Manuscript received 14 September 2023, in final form 6 December 2023, accepted 3 January 2024)

ABSTRACT: A simulation of a supercell storm produced for a prior study on tornado predictability is reanalyzed for the purpose of examining the fine-scale details of tornadogenesis. It is found that the formation of a tornado-like vortex in the simulation differs from how such vortices have been understood to form in previous numerical simulations. The main difference between the present simulation and past ones is the inclusion of a turbulent boundary layer in the storm's environment in the present case, whereas prior simulations have used a laminar boundary layer. The turbulent environment contains significant near-surface vertical vorticity ($\zeta > 0.03\ \mathrm{s}^{-1}$ at $z = 7.5$ m), organized in the form of longitudinal streaks aligned with the southerly ground-relative winds. The ζ streaks are associated with corrugations in the vertical plane in the predominantly horizontal, westward-pointing environmental vortex lines; the vortex-line corrugations are produced by the vertical drafts associated with coherent turbulent structures aligned with the aforementioned southerly ground-relative winds (longitudinal coherent structures in the surface layer such as these are well known to the boundary layer and turbulence communities). The ζ streaks serve as focal points for tornadogenesis, and may actually facilitate tornadogenesis, given how near-surface ζ in the environment can rapidly amplify when subjected to the strong, persistent convergence beneath a supercell updraft.

SIGNIFICANCE STATEMENT: In high-resolution computer simulations of supercell storms that include a more realistic, turbulent environment, the means by which tornado-like vortices form differs from the mechanism identified in prior simulations using a less realistic, laminar environment. One possibility is that prior simulations develop intense vortices for the wrong reasons. Another possibility could be that tornadoes form in a wide range of ways in the real atmosphere, even within supercell storms that appear to be similar, and increasingly realistic computer simulations are finally now capturing that diversity.

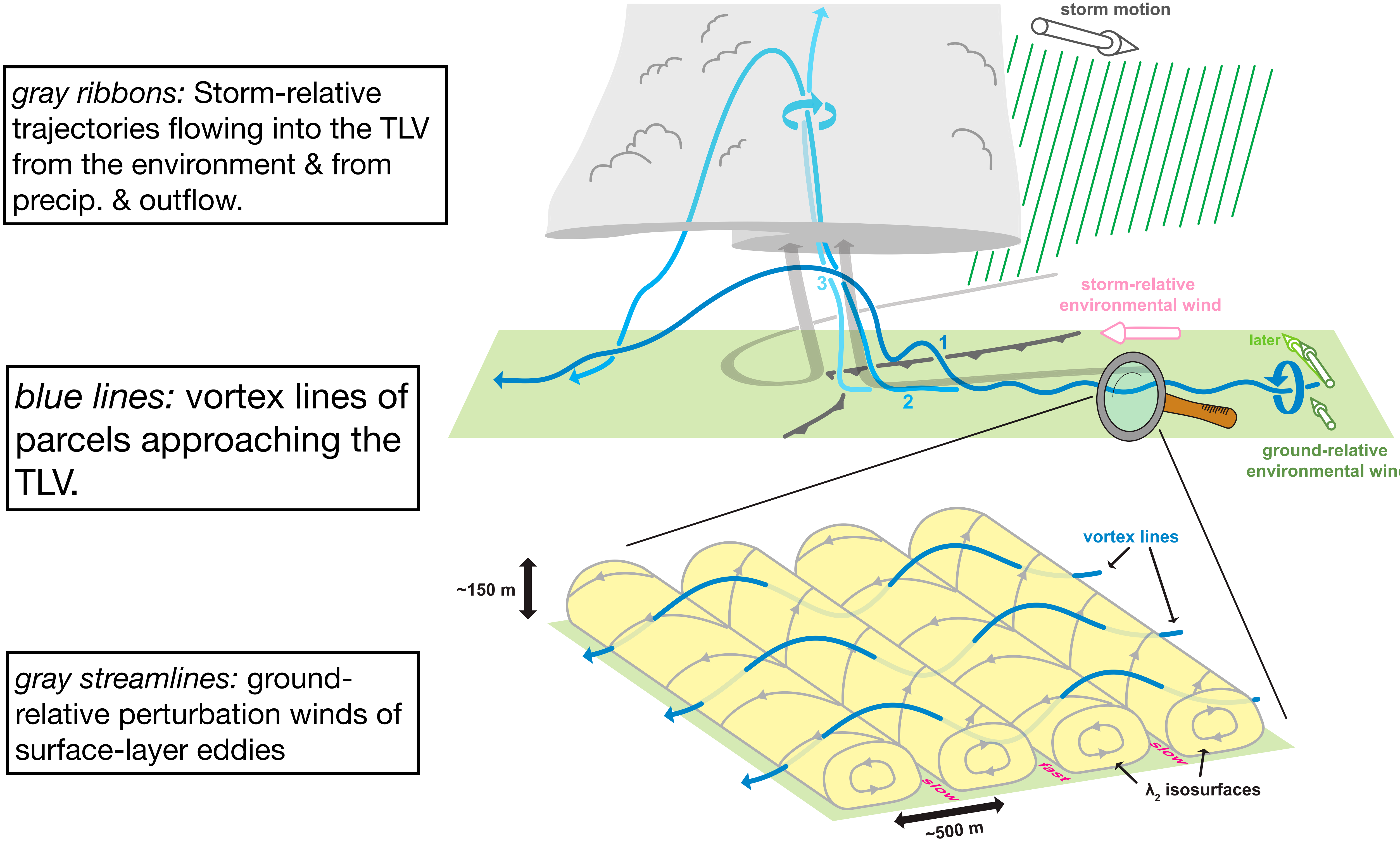


FIG. 25. Schematic summarizing the key aspects of the STORM9 simulation associated with tornadogenesis. The vortex lines (shades of blue) labeled "1," "2," and "3" can represent either a single vortex line at multiple times through a parcel approaching the developing TLV, a la Fig. 13, or different vortex lines at a single time drawn through locations increasing upstream of the developing TLV. The broad gray arrows indicate (storm-relative) trajectories feeding the TLV from the environment and from the precipitation and outflow (precipitation/outflow trajectories enter the developing TLV only once the flow associated with the intensifying ζ maximum becomes highly "axisymmetrized"). In the close-up of the environmental surface layer (bottom of figure), the gray streamlines indicate ground-relative perturbation winds associated with surface-layer eddies. The locations of alternating surface streaks of fast and slow wind speed are also indicated.

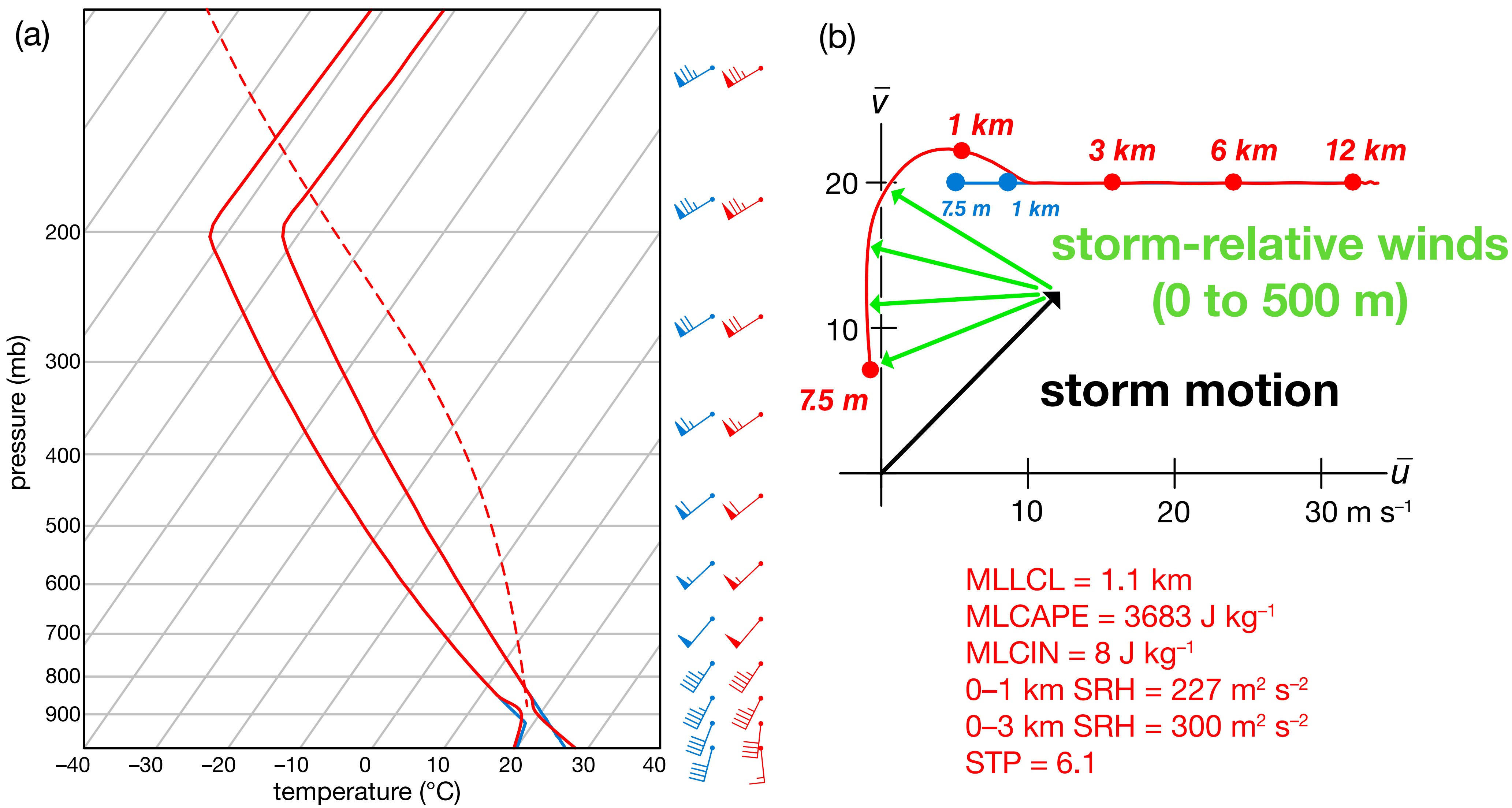


FIG. 1. (a) Domain-averaged soundings and ground-relative vertical wind profiles in the initial environment (blue) and quasi-steady environment after the 12-h spinup period, i.e., at the time that a warm bubble is introduced in order to initiate convection (red). Wind barbs are in knots. The dashed red curve is the pseudoadiabat followed by a parcel having the mean thermodynamic properties of the lowest 1 km. (b) Hodographs depicting the domain-averaged vertical wind profiles at $t = 0$ h (blue) and $t = 12$ h (red). Units on the axes are m s^{-1}; select altitudes along the hodographs are labeled ($z = 7.5$ m, 1, 3, 6, and 12 km). The black arrow indicates the ensemble mean storm motion. The green arrows indicate the storm-relative winds in the lowest 500 m. In both (a) and (b), the mean environments are independent of the random number seed used to impose random temperature perturbations at $t = 0$ h (i.e., the soundings and hodographs depict the mean environments in every ensemble member). The environmental parameters displayed in the lower right portion of the figure are for the quasi-steady environment at $t = 12$ h. MLLCL, MLCAPE, and MLCIN refer to mixed-layer (ML) lifting condensation level (LCL), CAPE, and convective inhibition (CIN), respectively. These were computed by lifting a parcel having the mean thermodynamic properties of the lowest 1 km. Adapted from M20.

Reflectivity at ~ 1000 m at 2 h in each simulation

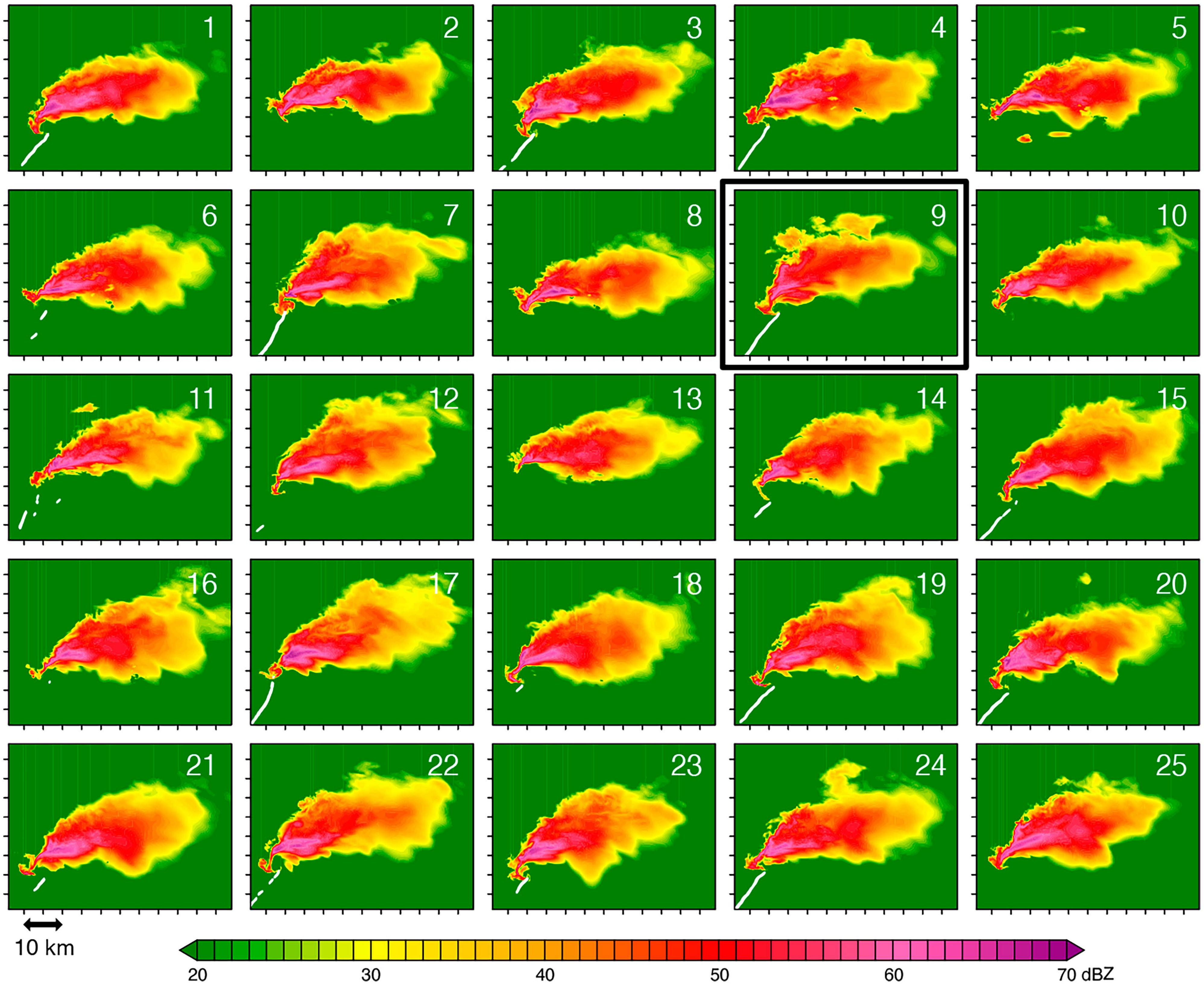


FIG. 2. Reflectivity at $z = 993$ m at 7200 s in each of the M20 ensemble members. White swaths are tornado tracks (the storms are approximately stationary on the model grid; the tracks are plotted by converting tornado locations to ground-relative locations). The numerals in each panel indicate the identification number of the ensemble member. Ensemble member number 9, the focus of this article, is indicated by the bold box. Adapted from M20.

white swaths are tornado tracks

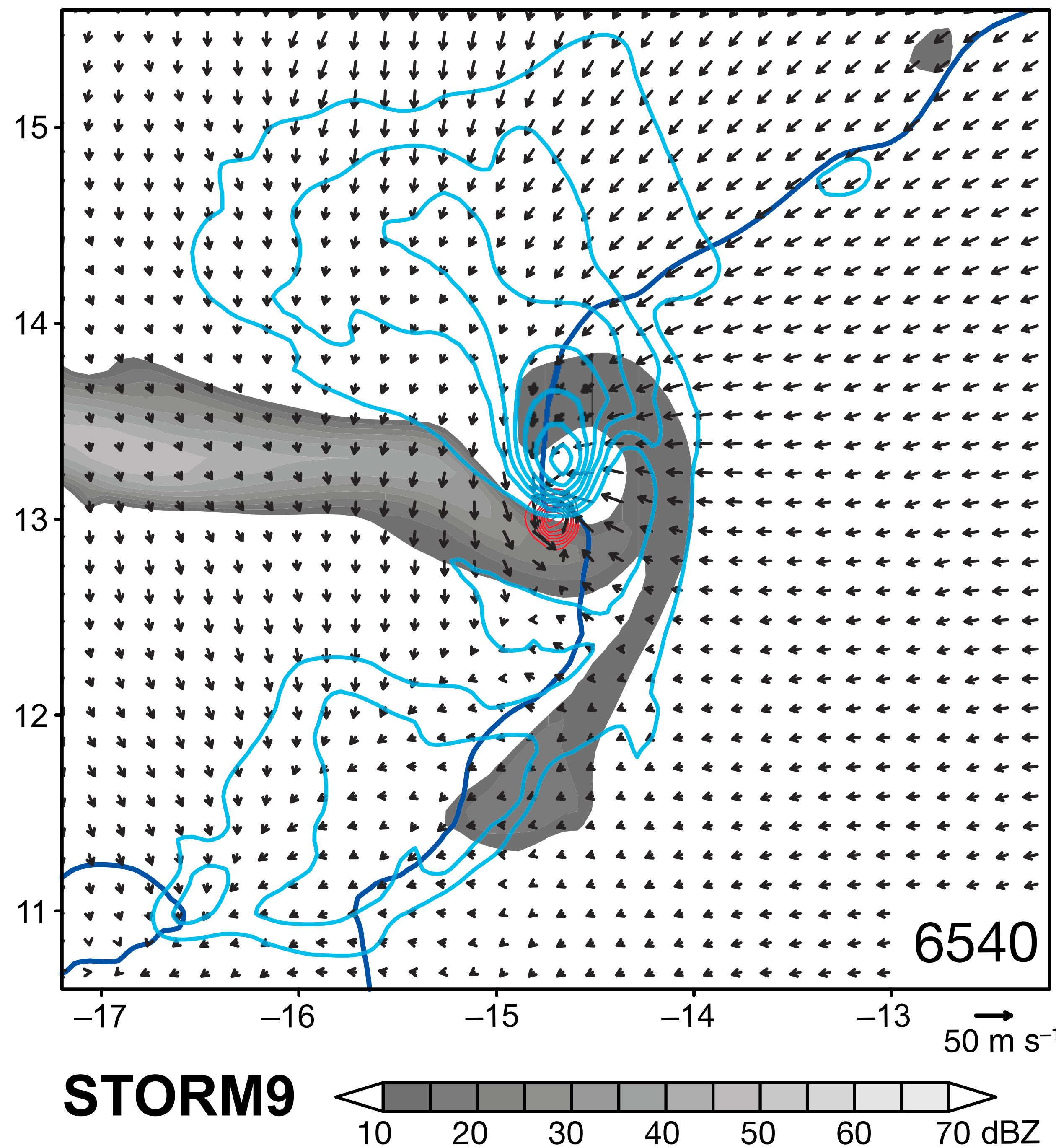


FIG. 3. The tornadic region in M20's ensemble member number 9 at 6540 s, at which time the TLV is at its peak intensity. Reflectivity (gray shading) and vertical velocity (cyan contours of 6, 12, 18 m s^{-1}, etc.) are displayed at z = 993 m. Horizontal storm-relative velocity vectors (every second grid point) and vertical vorticity (red contours of 0.1, 0.2, 0.3 s^{-1}, etc.) are displayed at z = 7.5 m. The $\theta'_\rho = -0.25$ K isopleth (dark blue contour) is overlaid to serve as a proxy for the gust-front location. Axis labels are in kilometers.

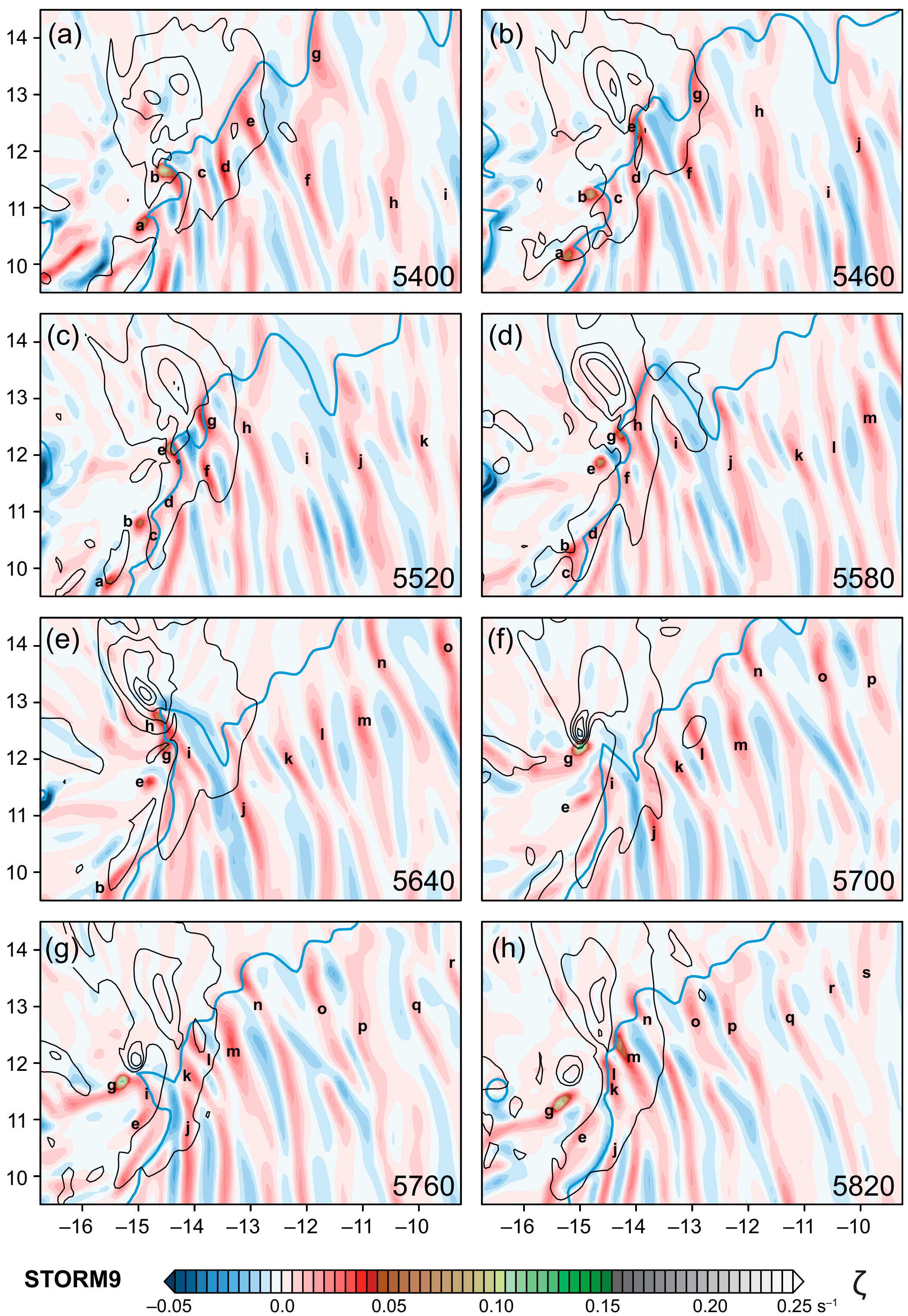


FIG. 5. Horizontal cross sections of ζ at z =7.5 m (shaded) and w at z = 522 m (black isotachs of 5, 10, 15, 20, 25 m s^{-1}) from (a) 5400 to (p) 6300 s at 60-s intervals in the STORM9 simulation. The $\theta'_\rho = -0.25$ K isopleth (bold blue contours) is overlaid to serve as a proxy for the gust front location. Axis labels are in kilometers. Letters identify particular ζ maxima to facilitate their tracking from panel to panel; the "m" anomaly attains TLV ζ and wind speed thresholds at 6240 s.

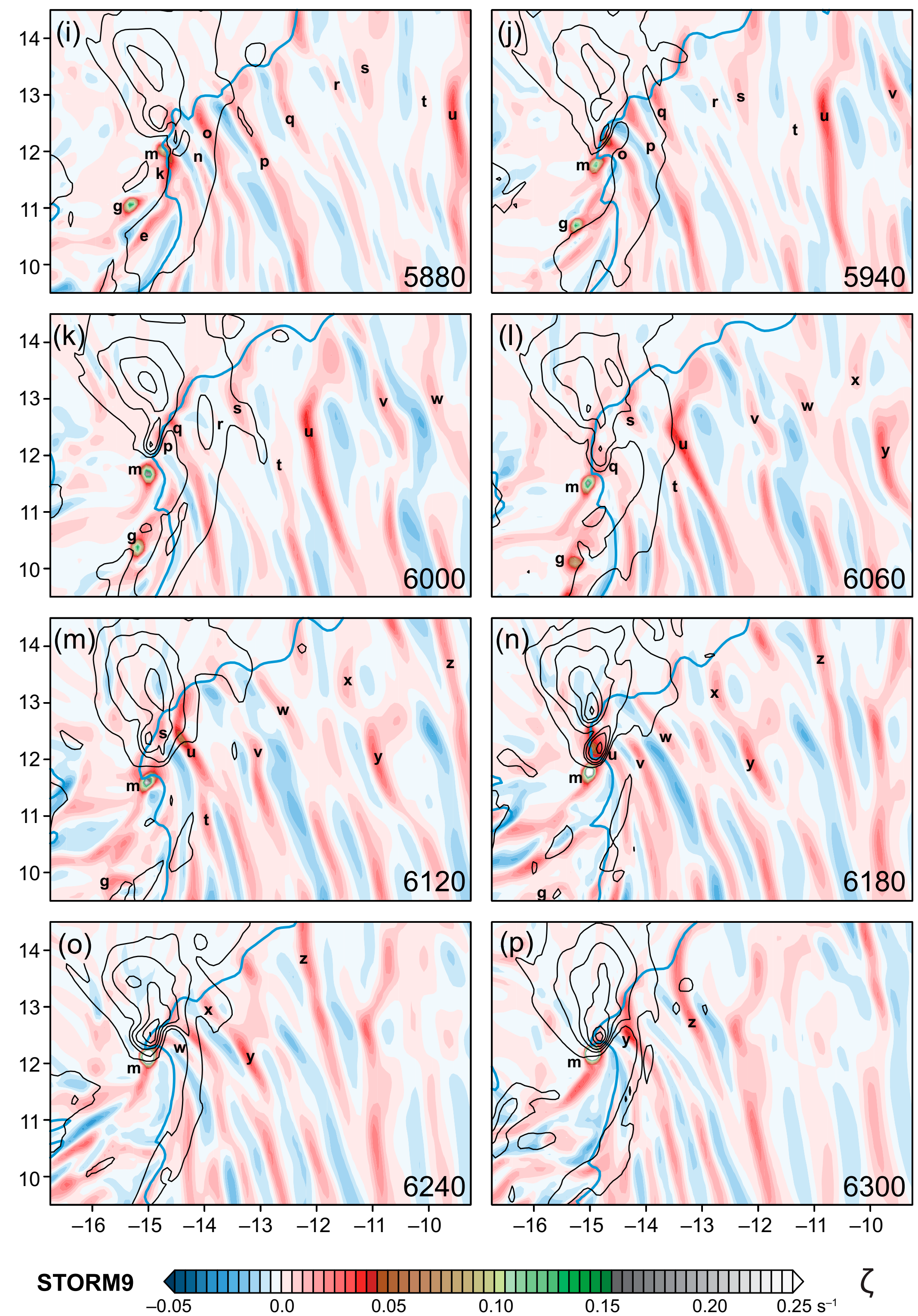
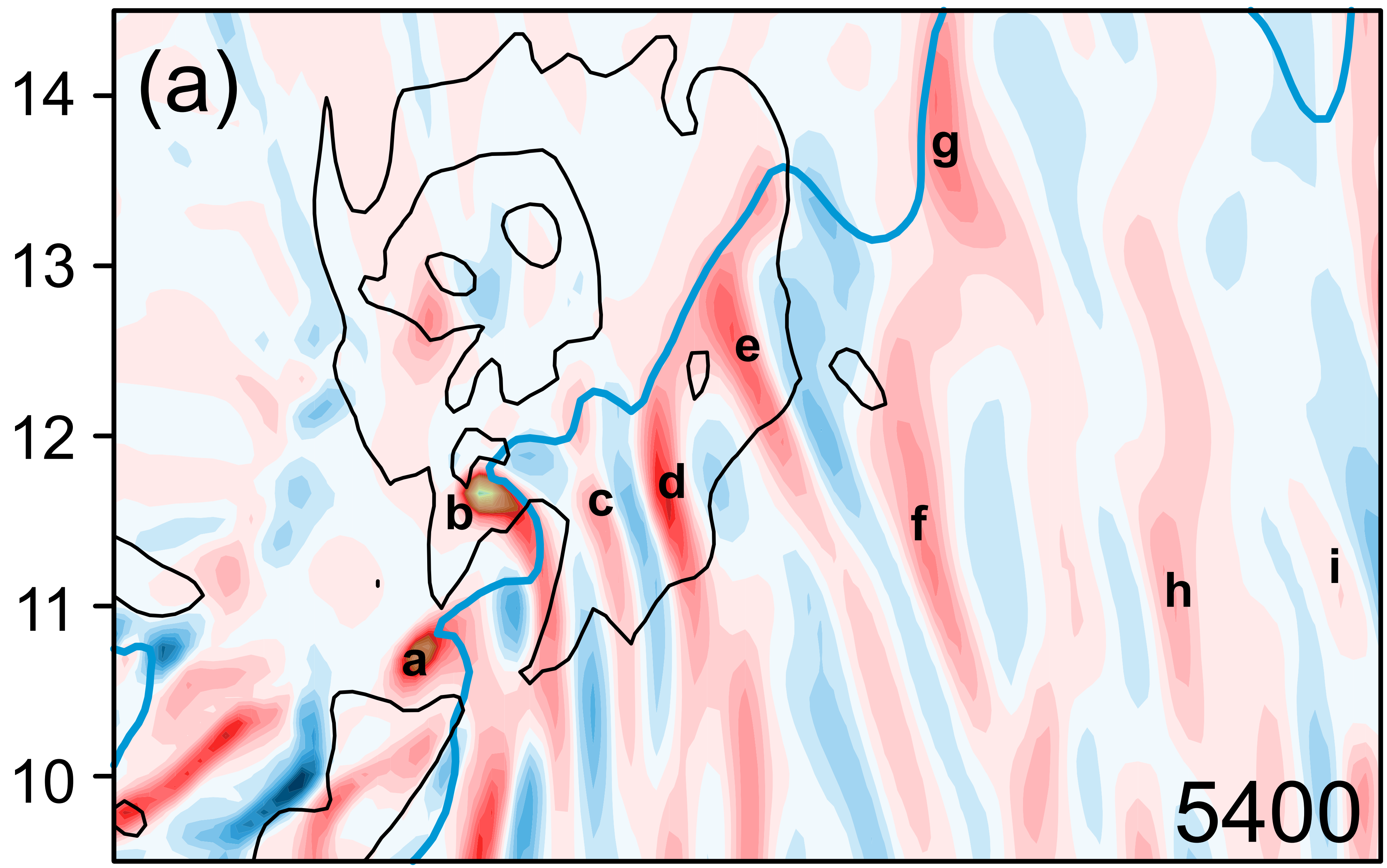


FIG. 5. (*Continued*)



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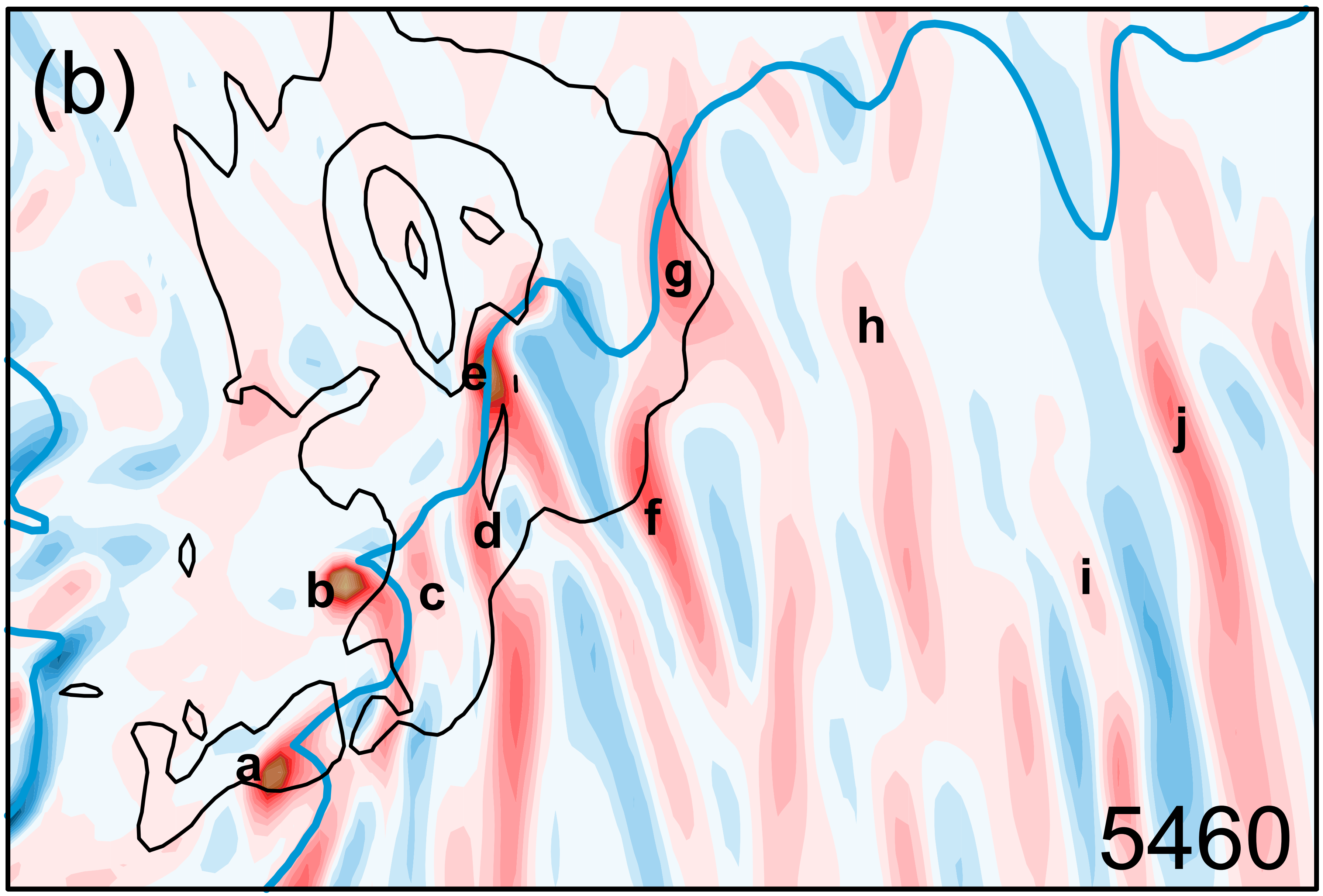

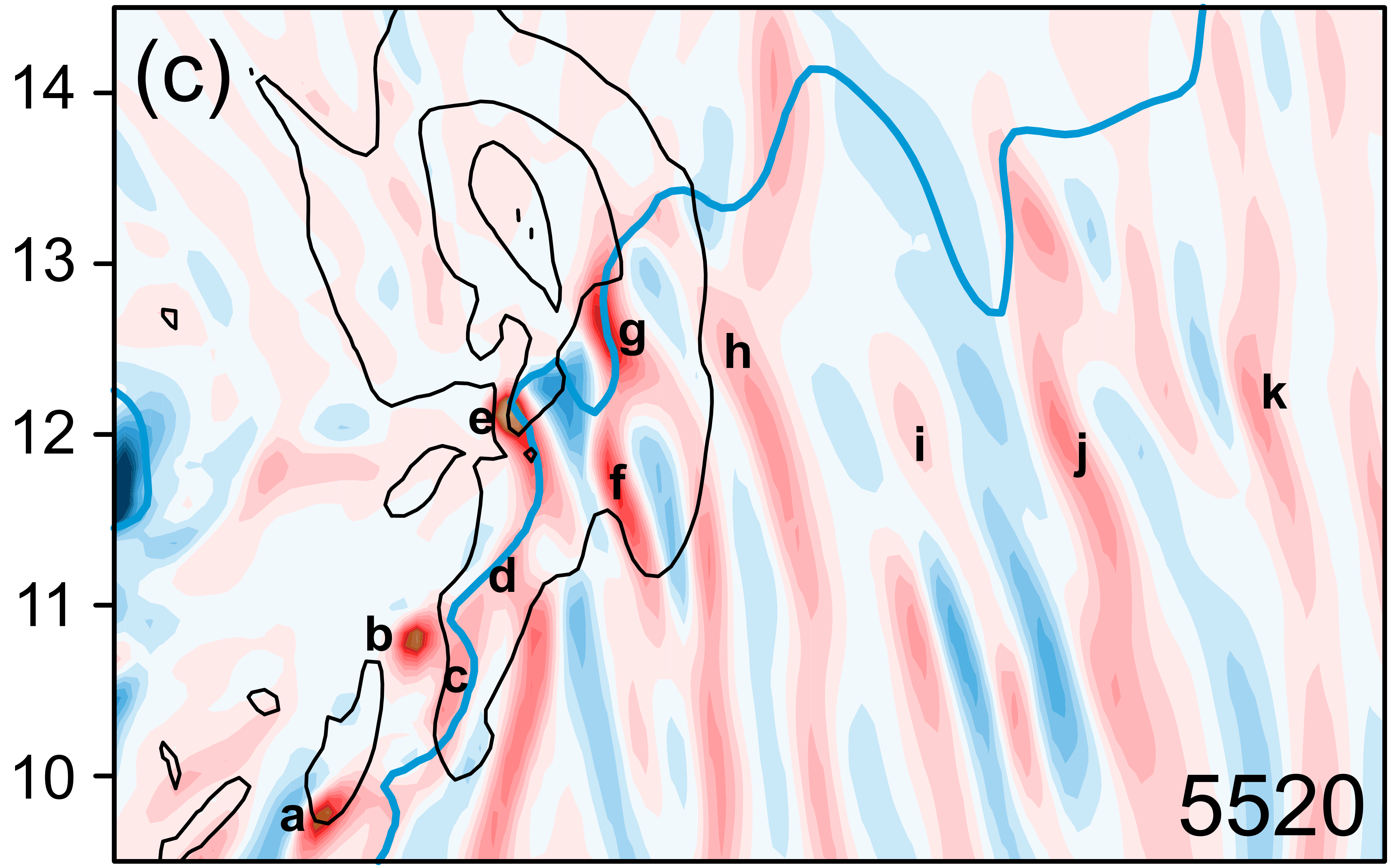

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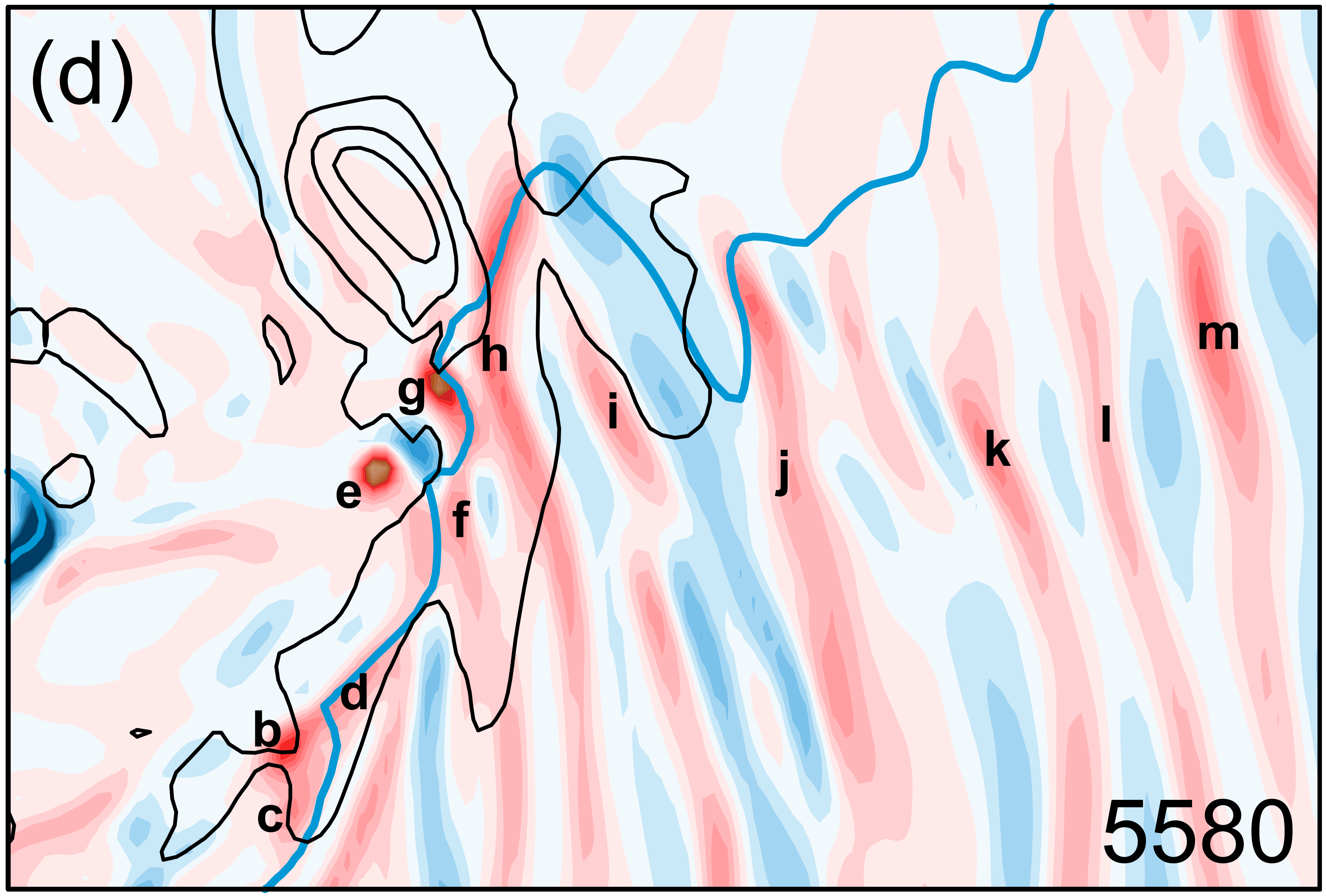
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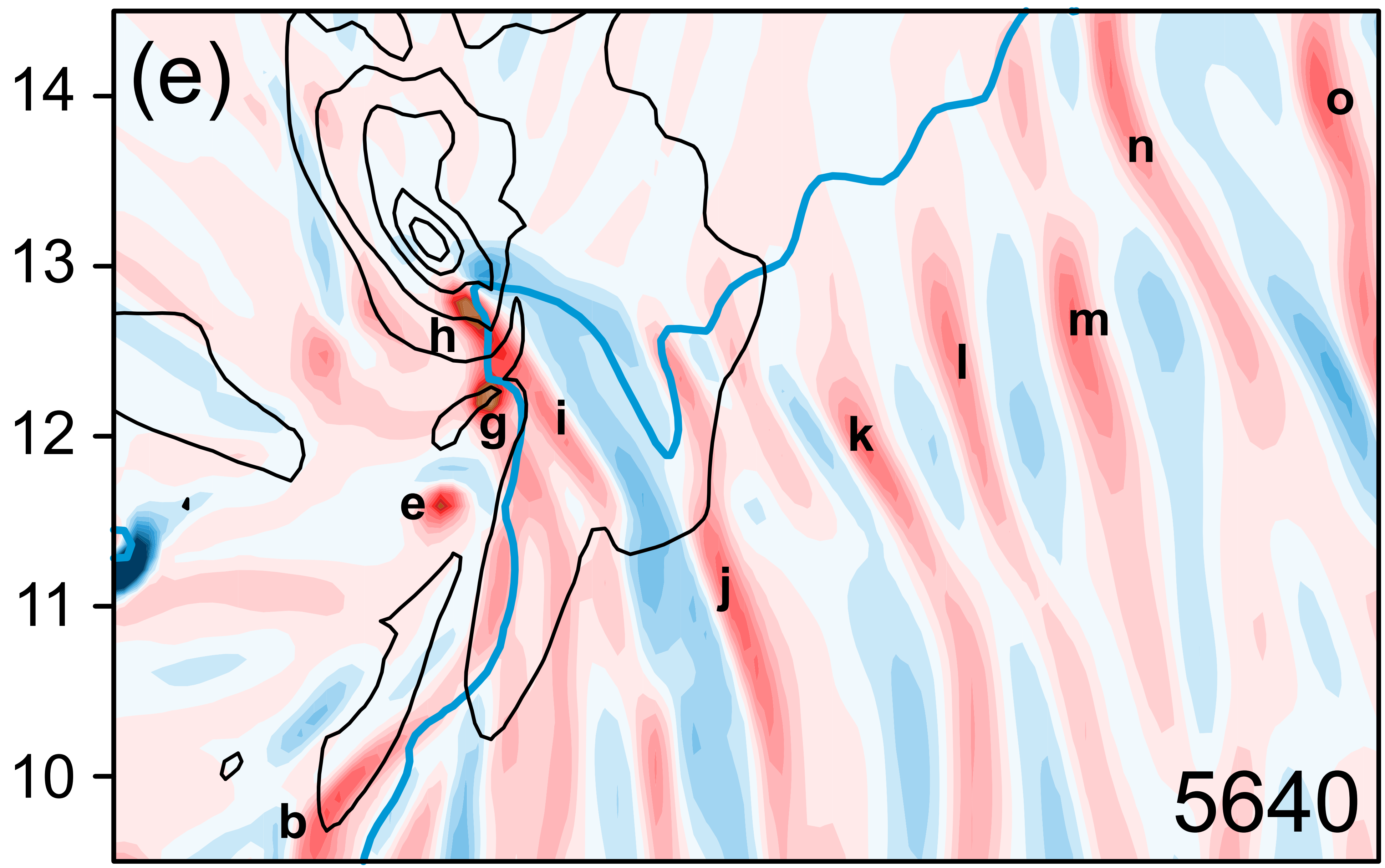
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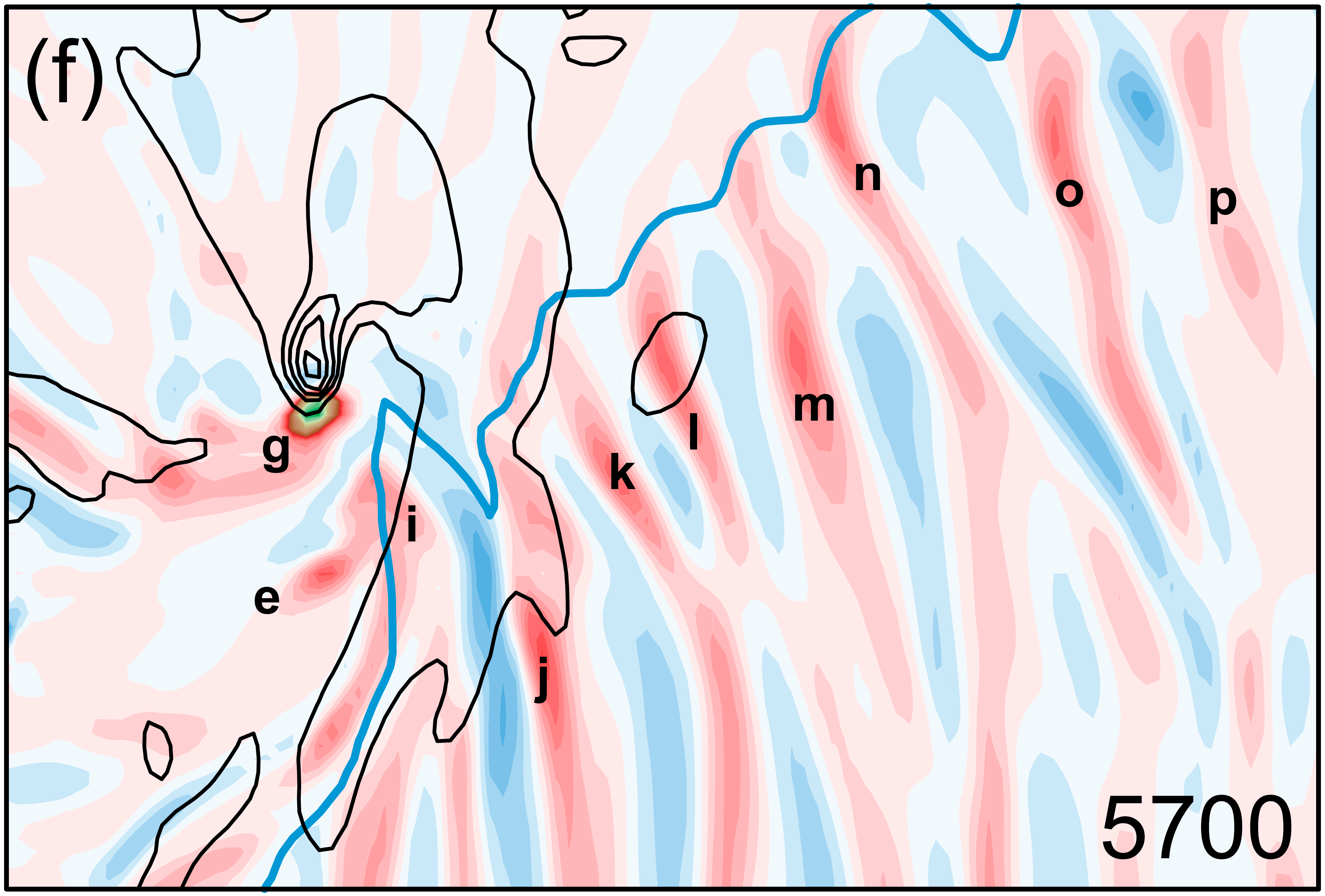
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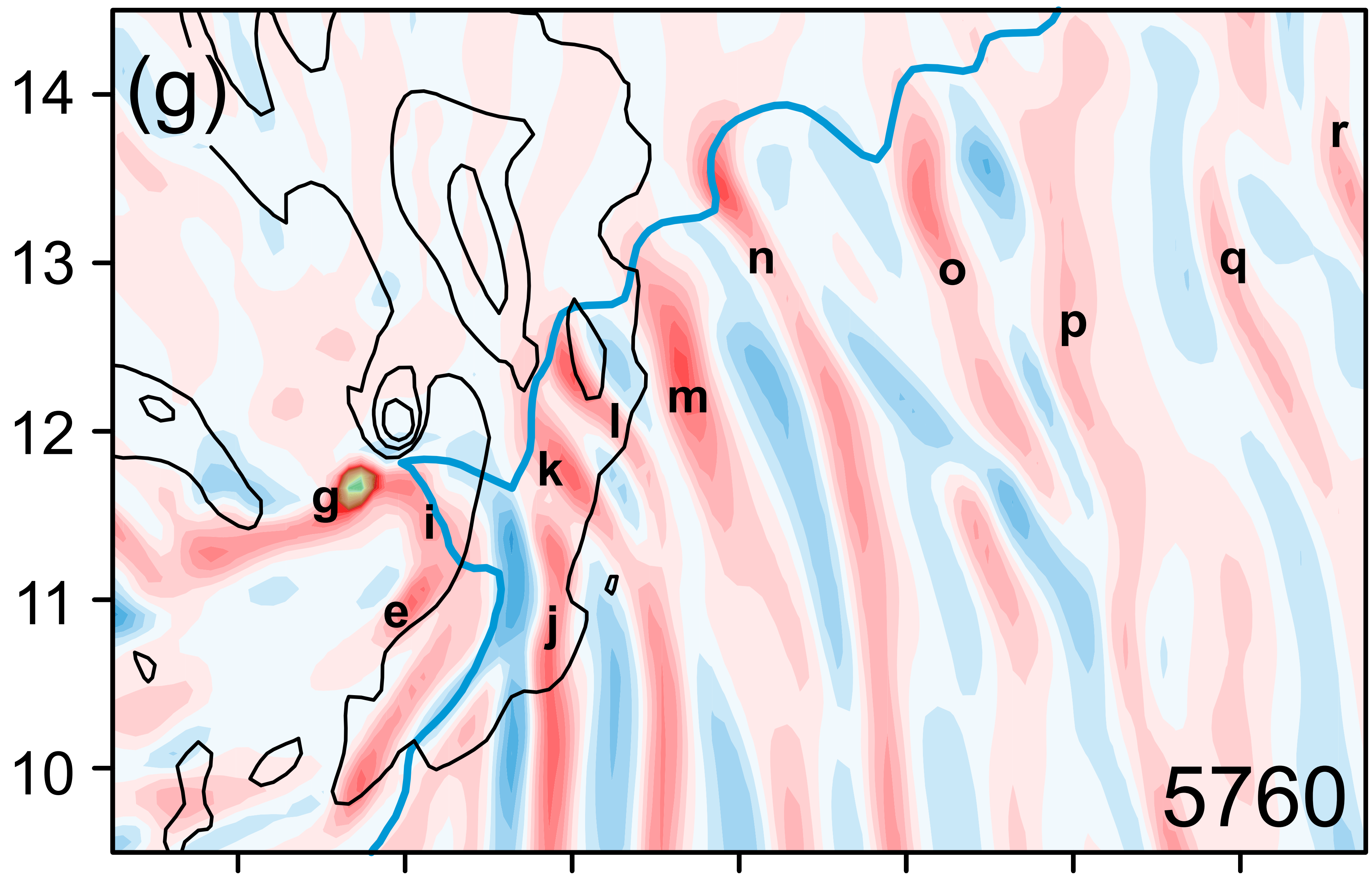
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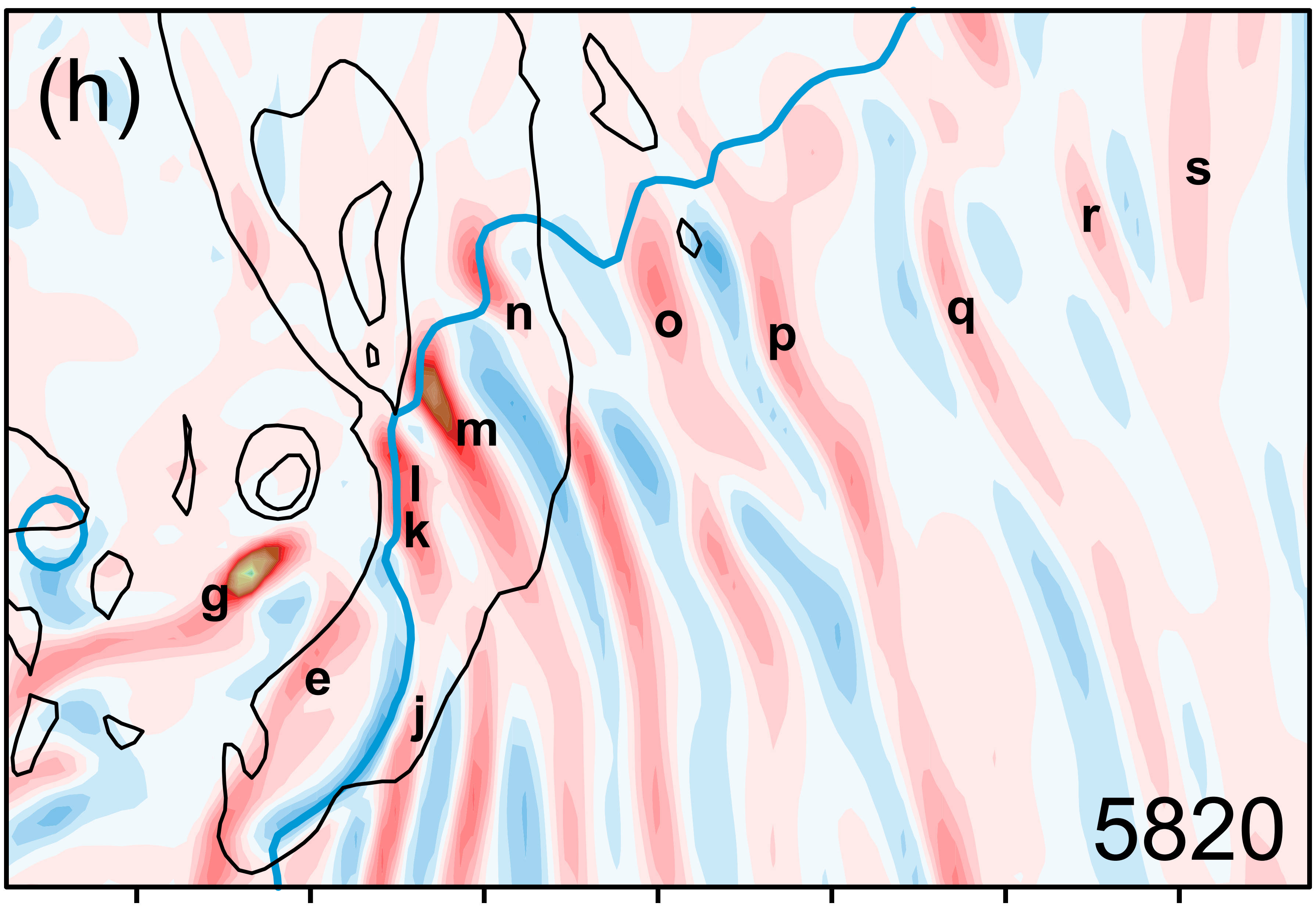

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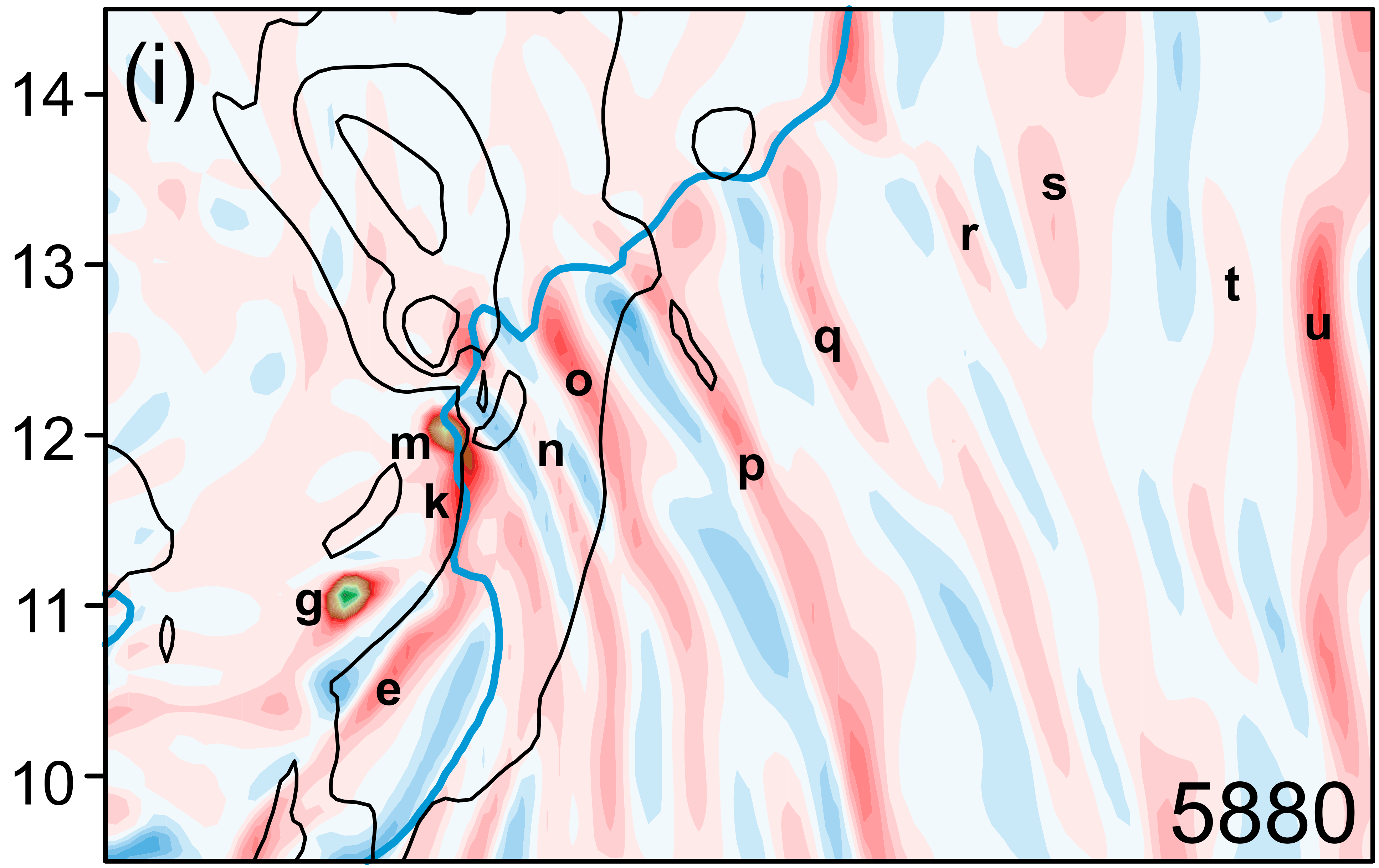

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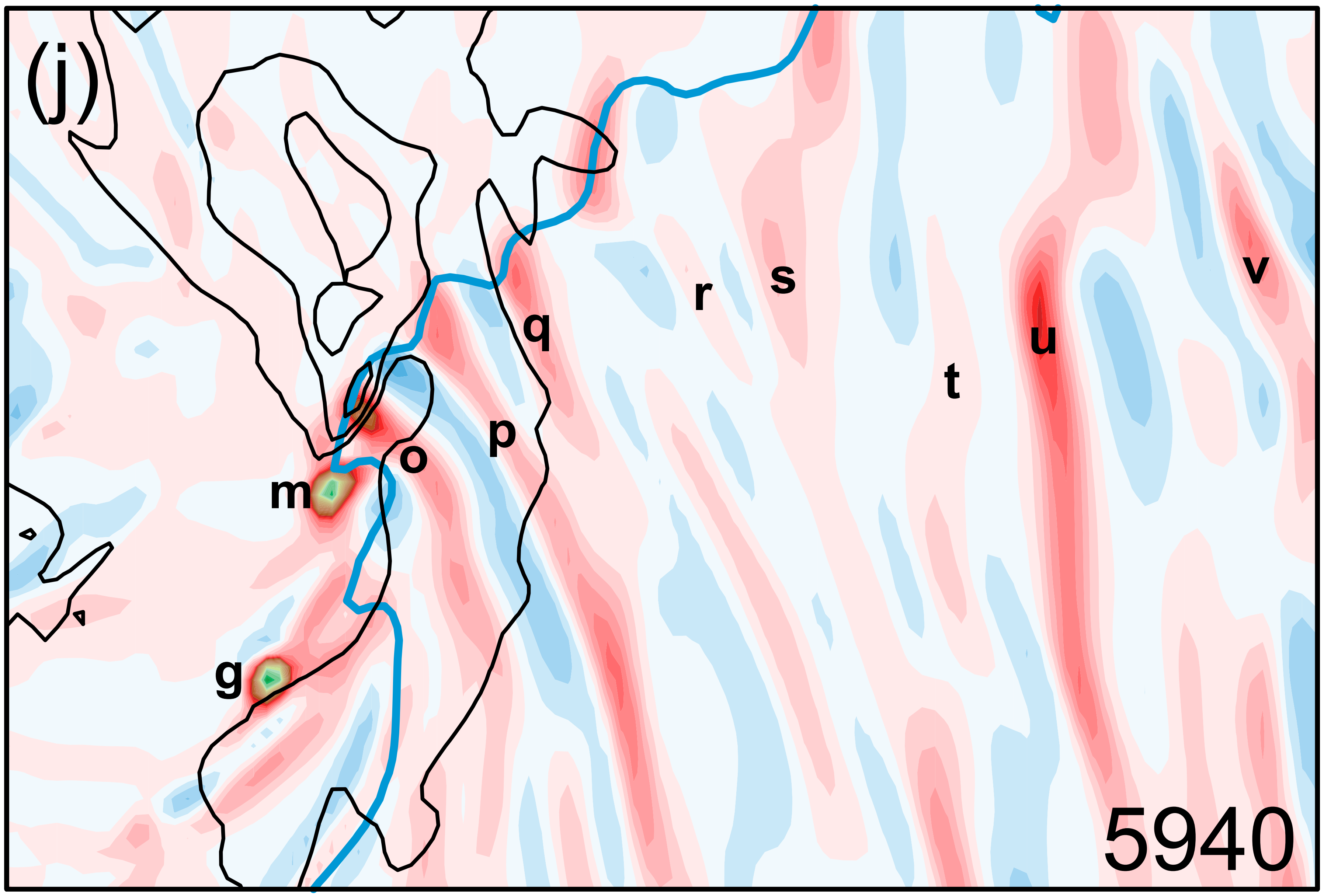

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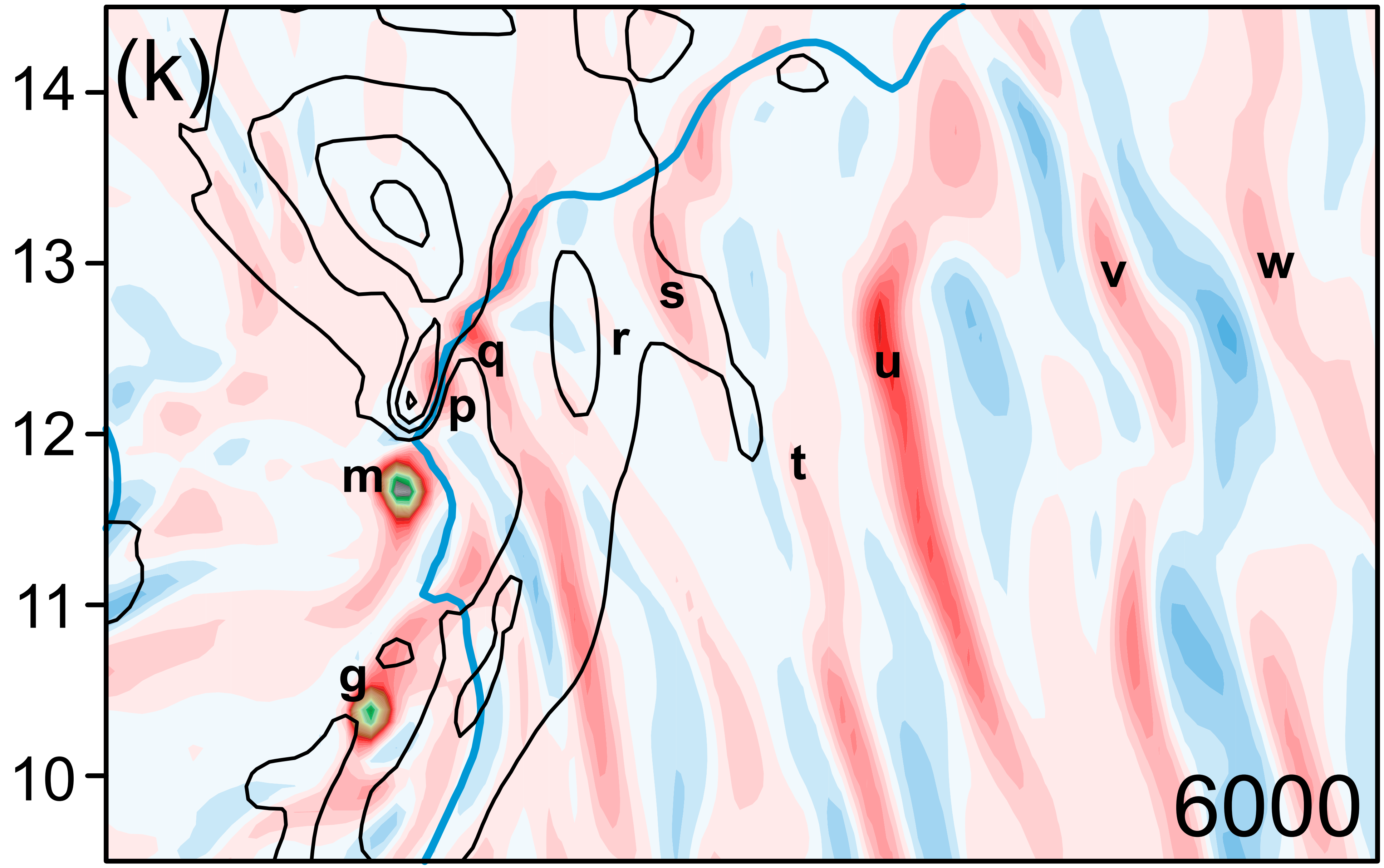
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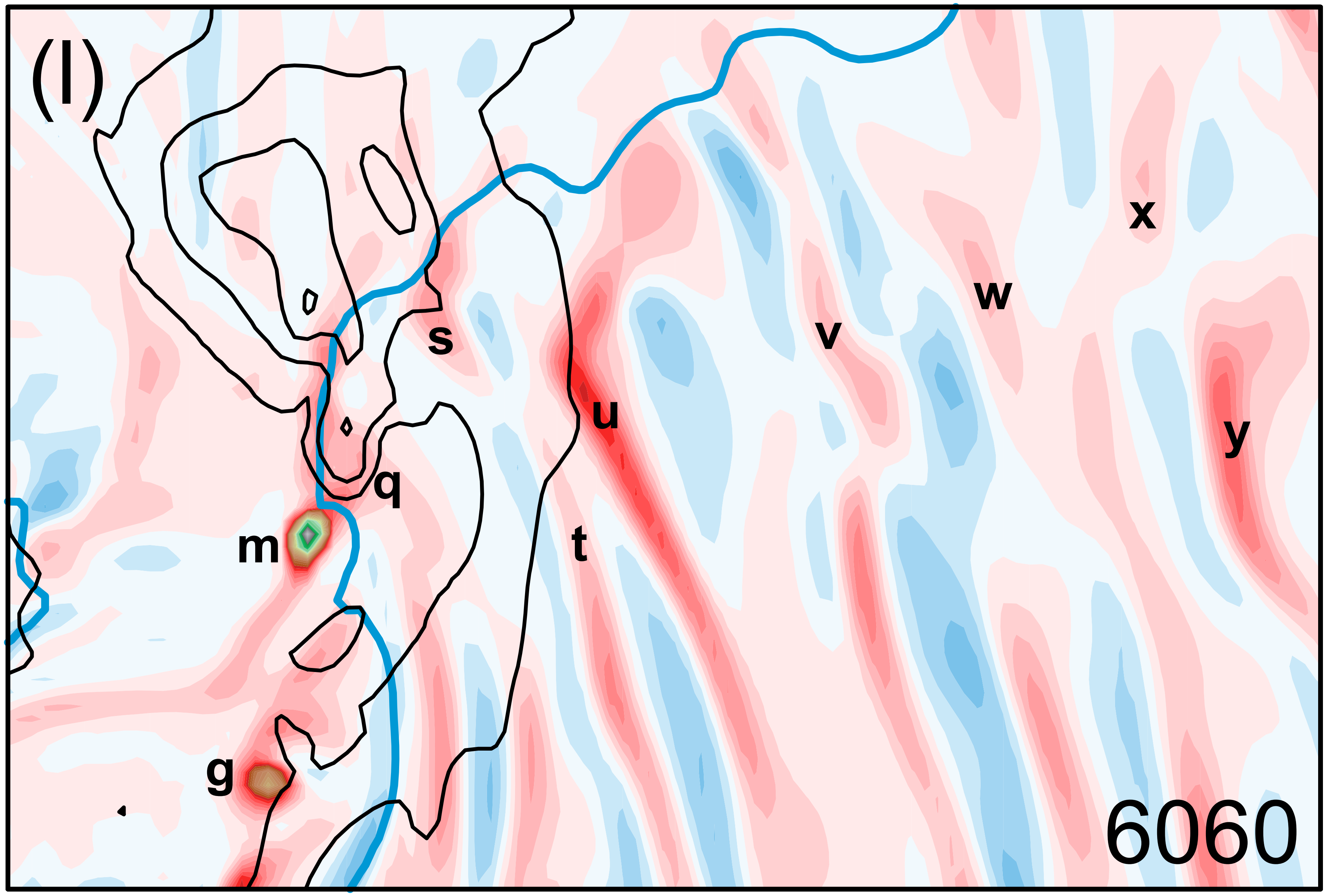

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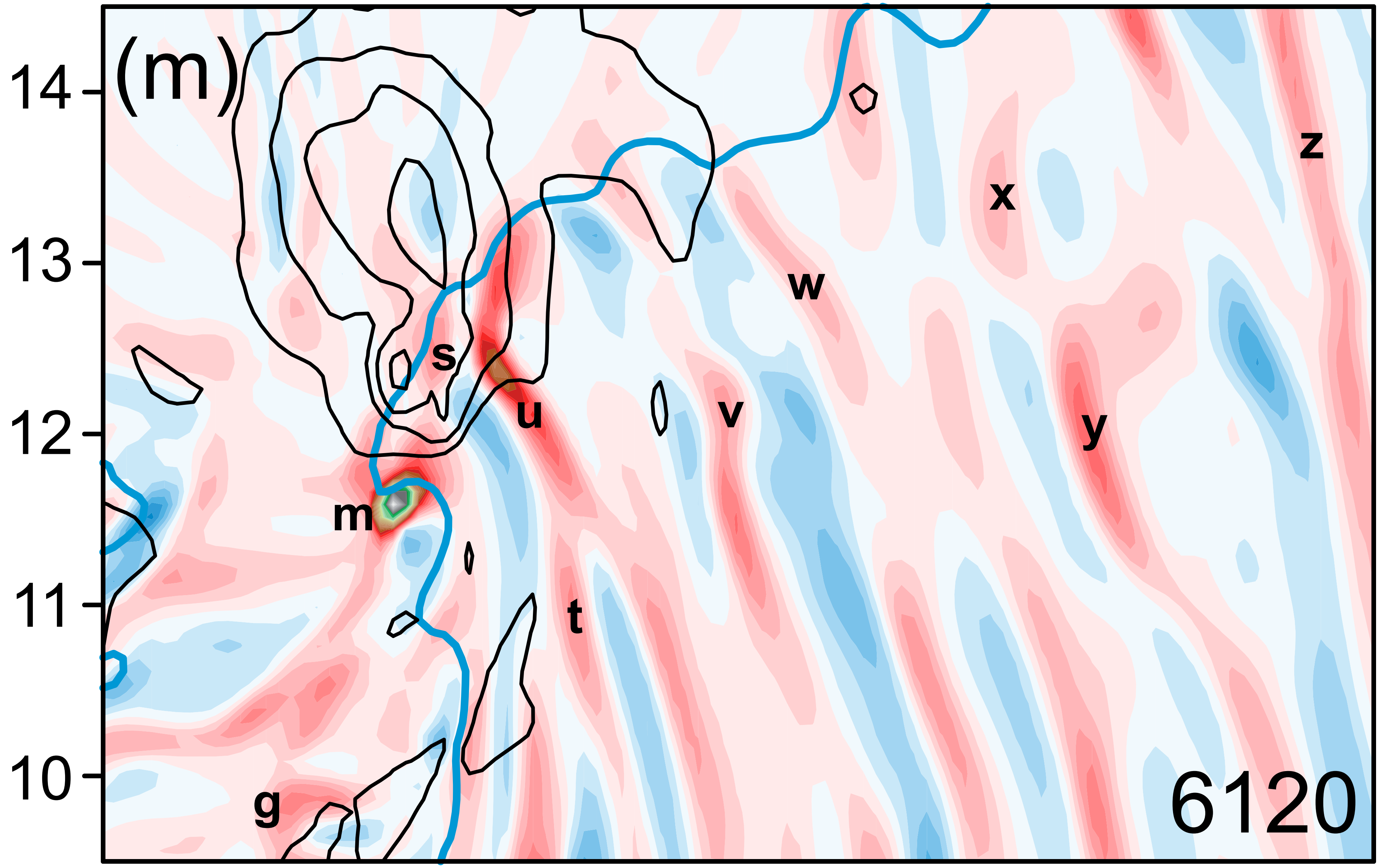
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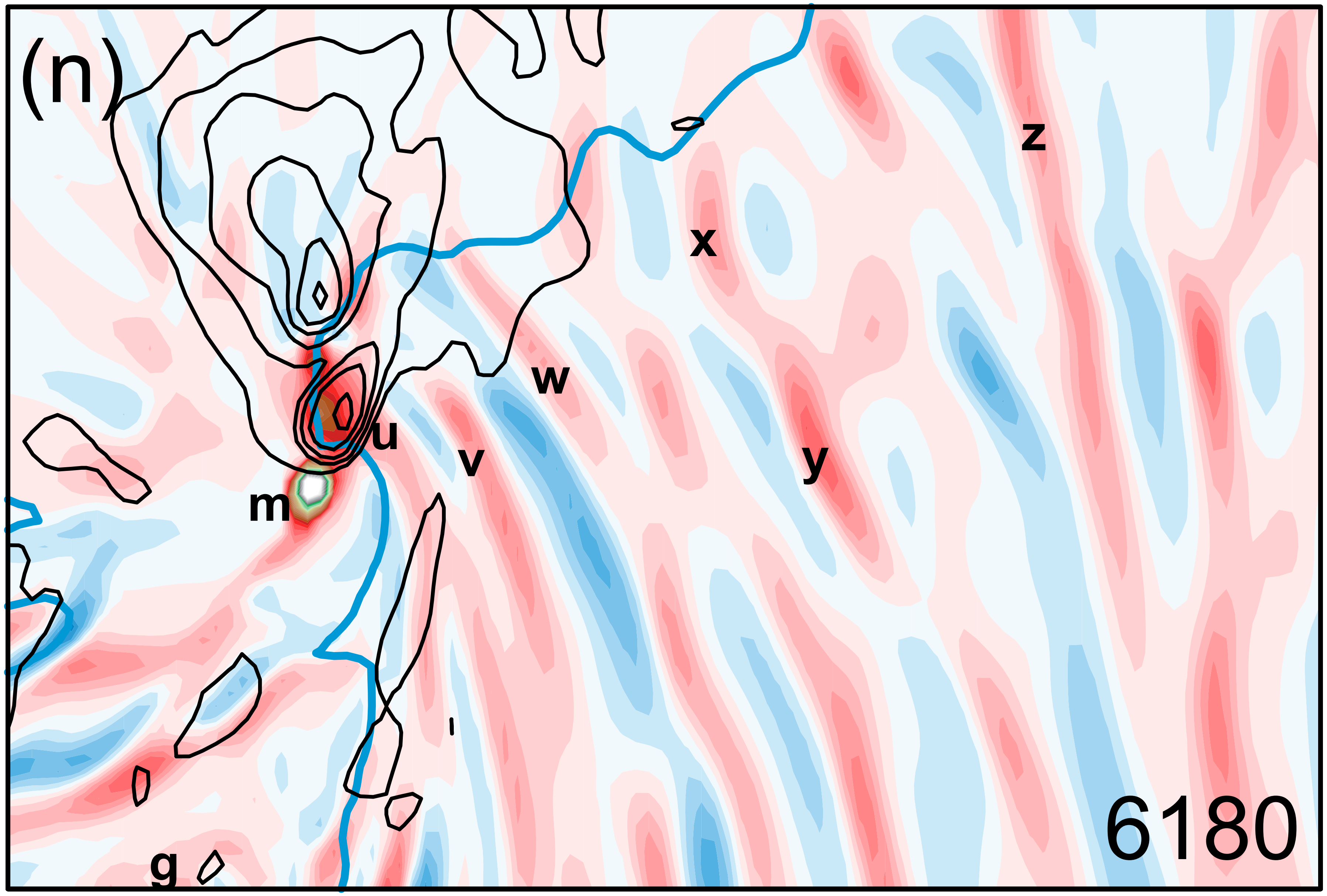
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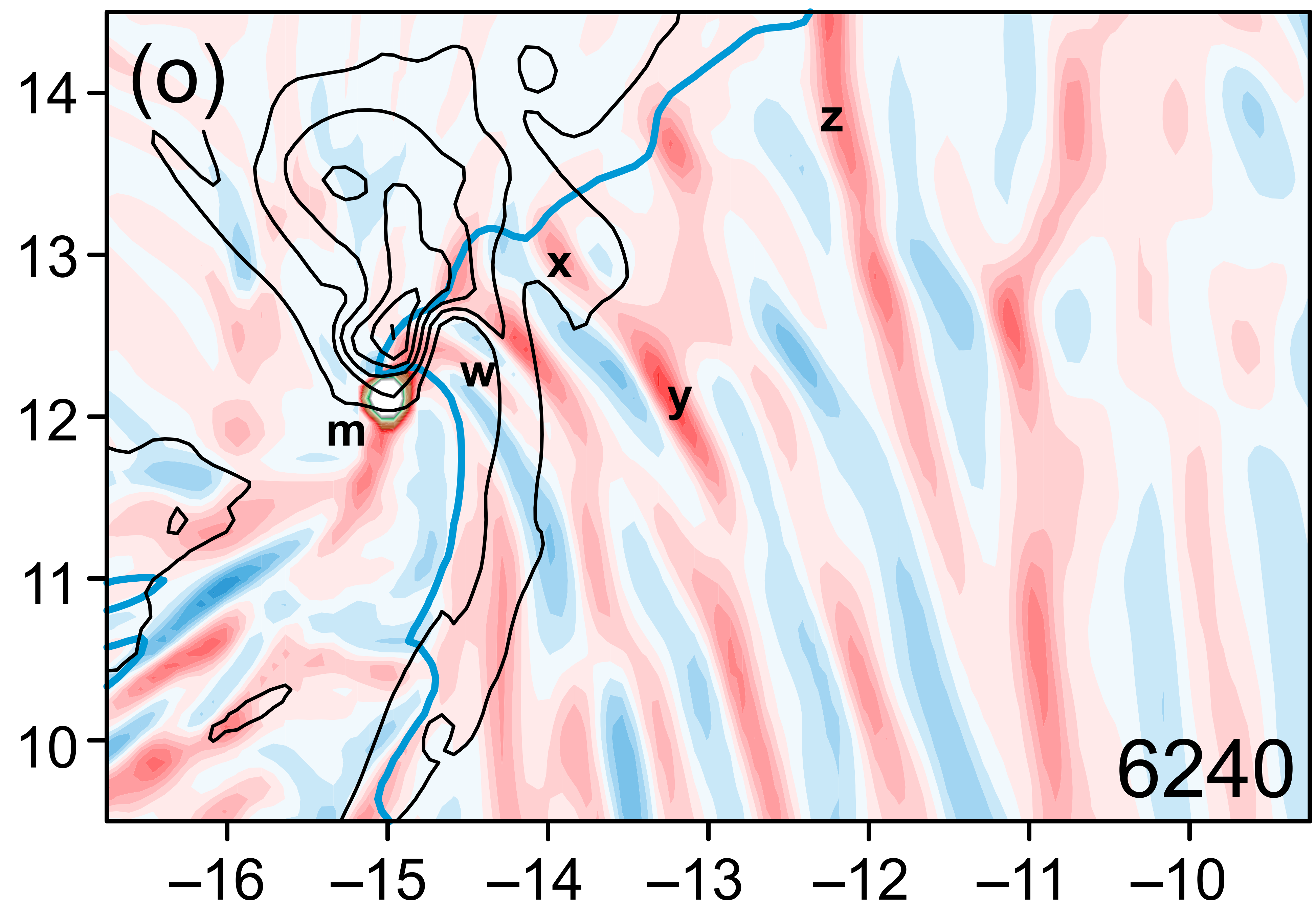

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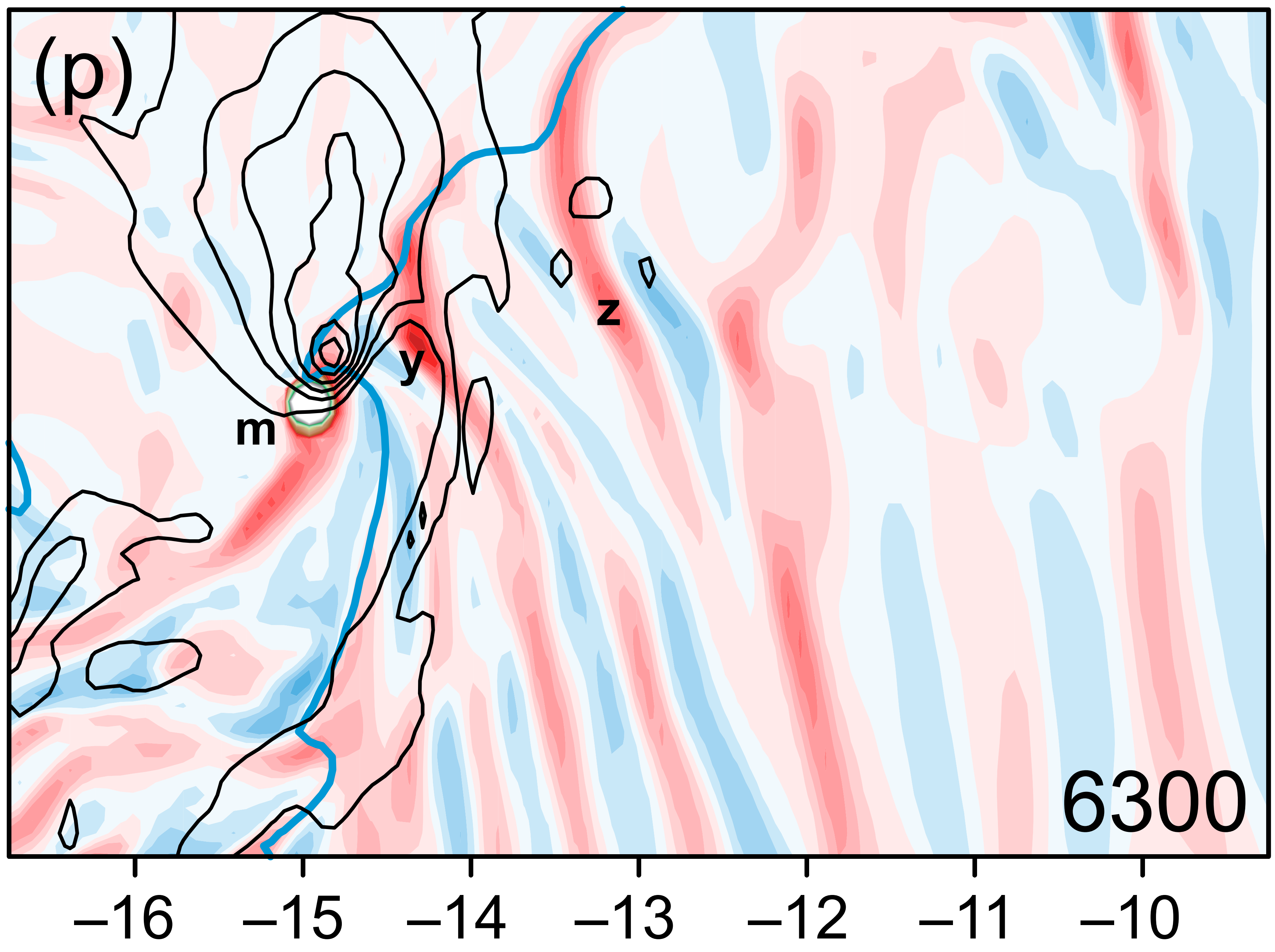
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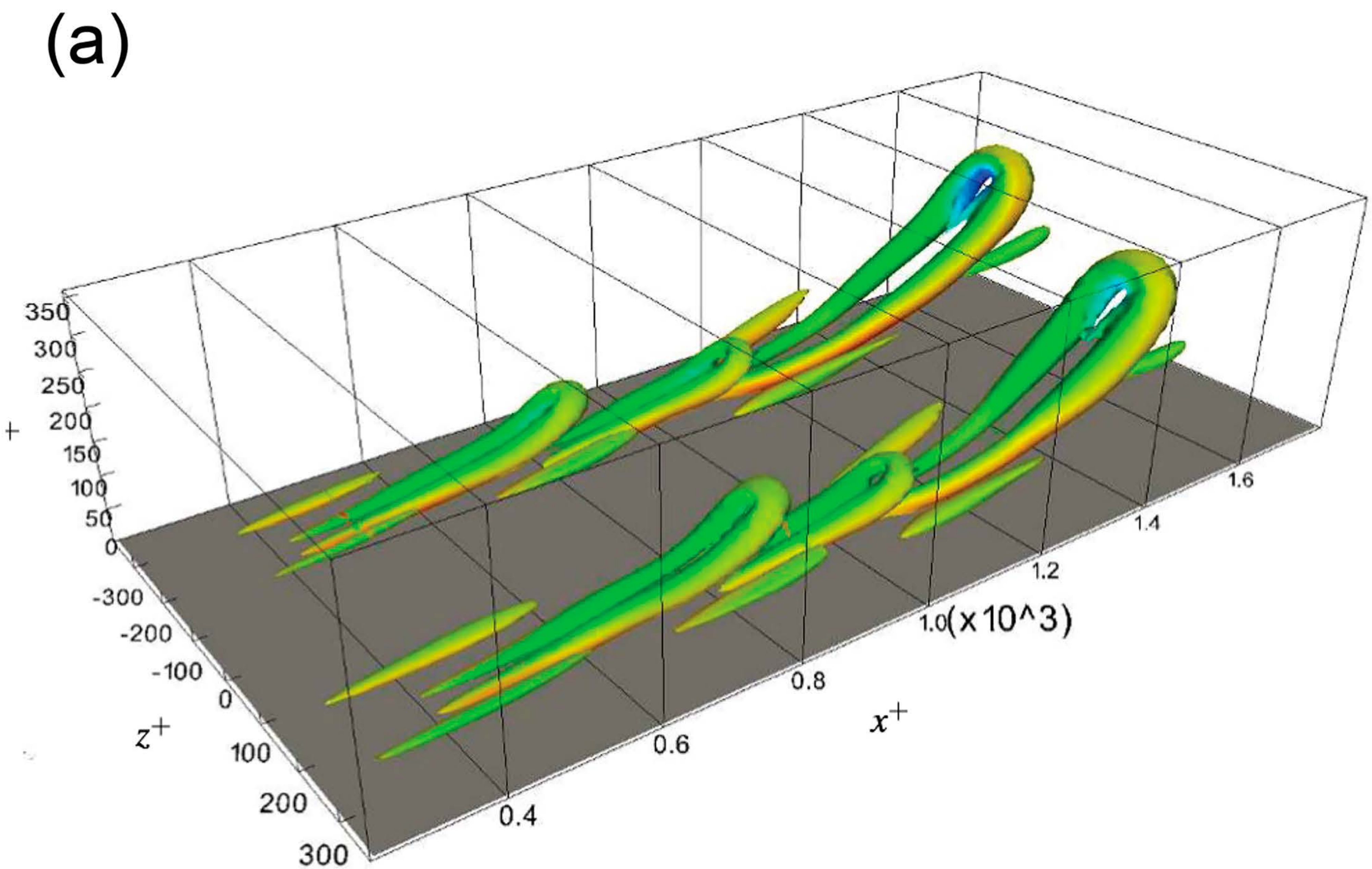
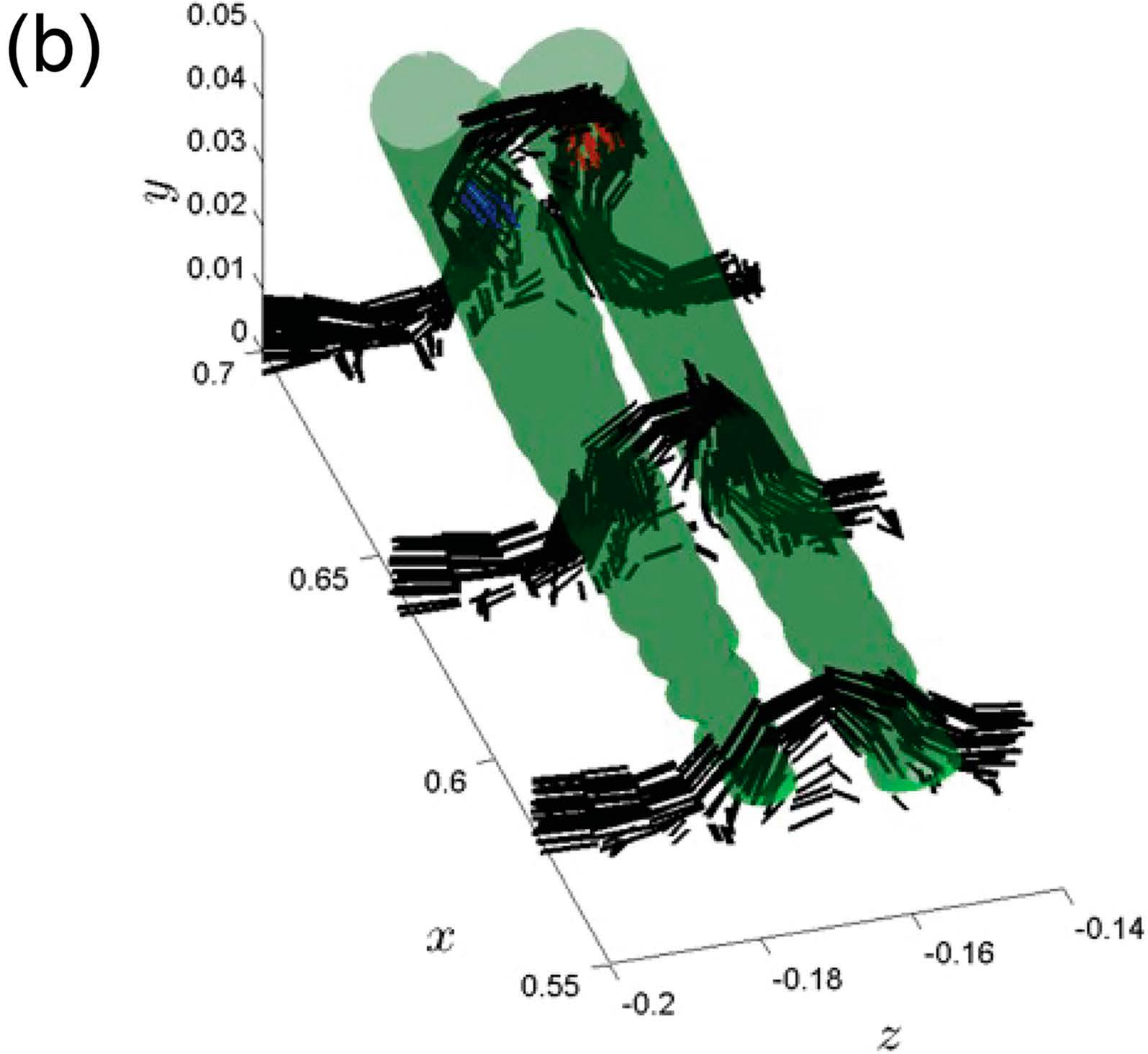
Samples of visualizations of hairpin vortices and other coherent structures found in the literature.

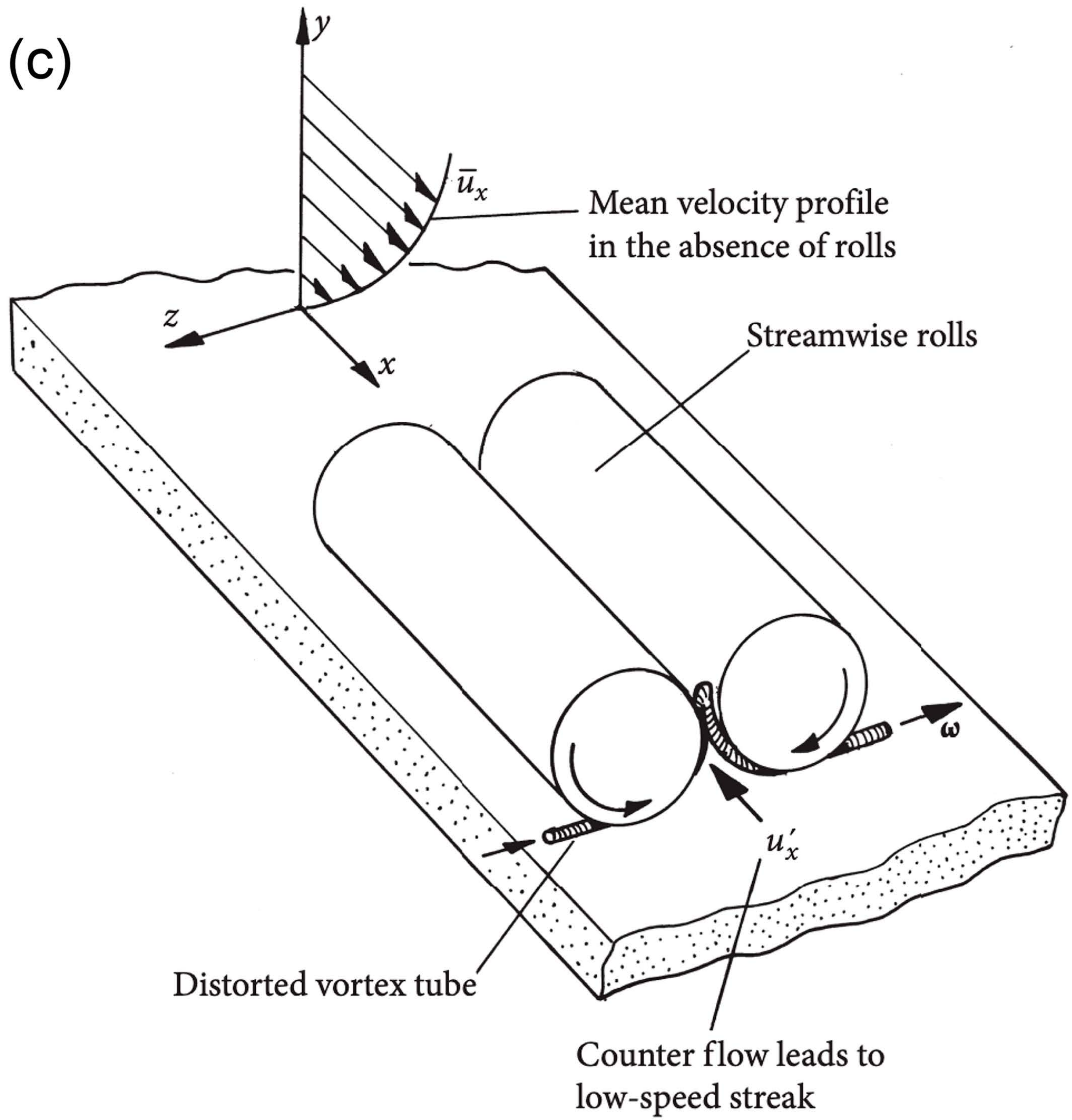


Hairpin vortices in a channel flow



A pair of counterrotating, coherent (and vortical) structures (green isosurfaces) and accompanying vortex filaments (black)

(c)

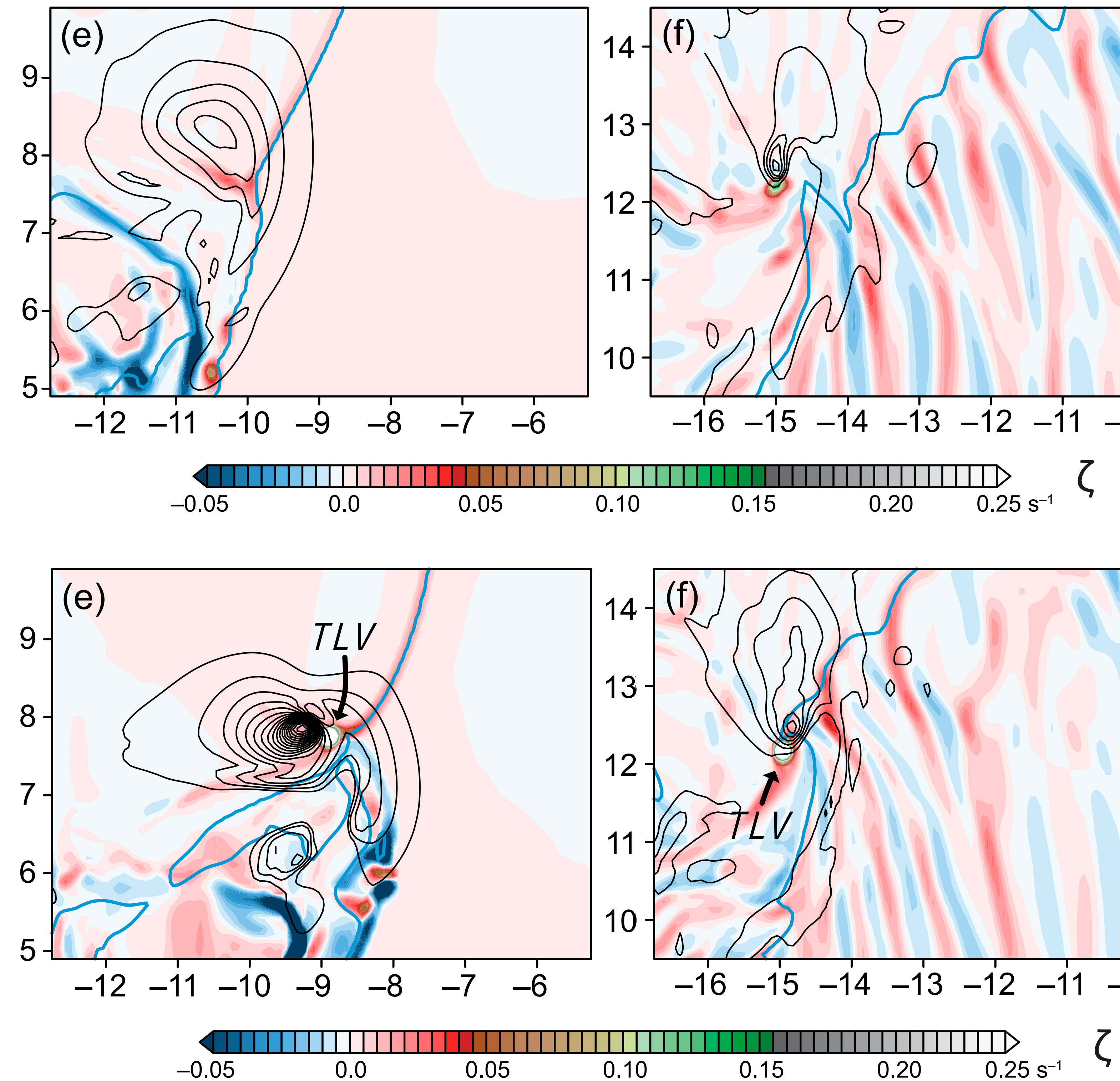


Coherent structures in the surface layer with an attendant vortex line.

How do tornadoes form in simulations with a laminar (non-turbulent) boundary layer?

5700 s

6300 s



TLV=tornado-like vortex

A close inspection of

- (i) the details of the evolution of the vertical vorticity field,
- (ii) trajectories,
- (iii) Lagrangian analyses of the sources of circulation, and
- (iv) vortex lines

tells a different story from the decades-old consensus.

- (i) The details of the evolution of the vertical vorticity field (ζ):
    - The initial ζ amplification occurs within longitudinal ζ streaks in the environmental air mass, rather than within the outflow or along the gust front.
- (ii) Trajectories
    - The incipient TLV is fed exclusively by environmental air parcels until axisymmetrization occurs
- (iii) Lagrangian analyses of the sources of circulation:
    - The TLV's primary circulation source is vorticity in the environment, or environmental vorticity modified by surface drag, as opposed to baroclinically generated circulation.
- (iv) Vortex lines…
- that are constructed through the TLV also originate in the environment.

It would seem that at least one of the following must be true:

1) prior supercell simulations that have used laminar, horizontally homogeneous environmental boundary layers develop TLVs (if their resolution permits), and perhaps also near-surface mesocyclones, for the wrong reasons;
2) the M20 supercell simulations develop TLVs for the wrong reasons;
3) supercell tornadoes form in a wide range of ways in the real atmosphere, even within supercells that appear to be similar, and increasingly realistic numerical simulations are finally now capturing that diversity (if true, additional environmental ingredients might be worthy of consideration in tornado forecasting).