Outflow and inertial stability in hurricanes Iselle and Julio (2014) and Joaquin (2015)

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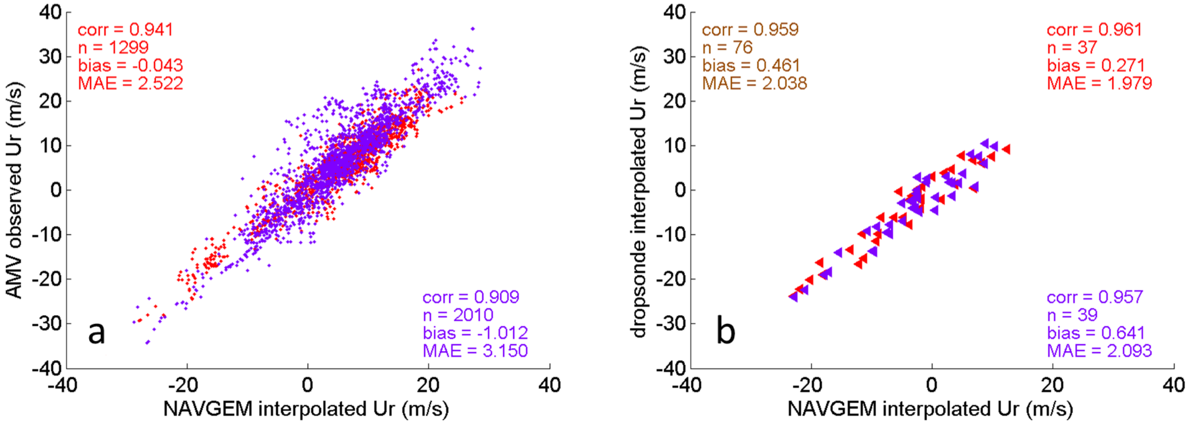
Goals and objectives

- Examine outflow of three major hurricanes in two ocean basins (East Pacific and North Atlantic)
- Explore changes in outflow magnitude and direction over time
  - Use azimuthal and radial Hovmöller diagrams as primary analysis tool
- Connect outflow qualitatively with synoptic-scale environmental features
  - Focus on shortwave troughs and ridges
- Calculate inertial stability I^2 and compare to outflow
  - Hypothesis was that outflow would be found in regions where I^2 was lowest

Data and methods

- Took gridded wind fields (u,v) from Navy Global Environmental Model (NAVGEM) analyses every 6 hours during each storm's life cycle
  - Iselle (31 July – 09 August 2014)
  - Julio (04 – 15 August 2014)
  - Joaquin (27 September – 07 October 2015)
- Converted NAVGEM Cartesian u, v to polar coordinates u_r and u_ϑ,
  - Convention that u_r positive outward from storm center and u_ϑ positive counterclockwise
  - Horizontal grid spacing: 0.5° x 0.5° lat-lon
  - Vertical spacing: standard pressure levels (1000 mb up to 100 mb)
- Examined the quality of NAVGEM winds
  - Compared u_r component of NAVGEM winds to u_r component of atmospheric motion vectors (AMVs http://tropic.ssec.wisc.edu/archive/) and GPS dropsondes released during NOAA G-IV missions into Iselle and Julio
- Found very high linear correlation (0.94 for Iselle and 0.91 for Julio) and small biases (0.4 m s^{-1} for Iselle and -1.0 m s^{-1} for Julio)

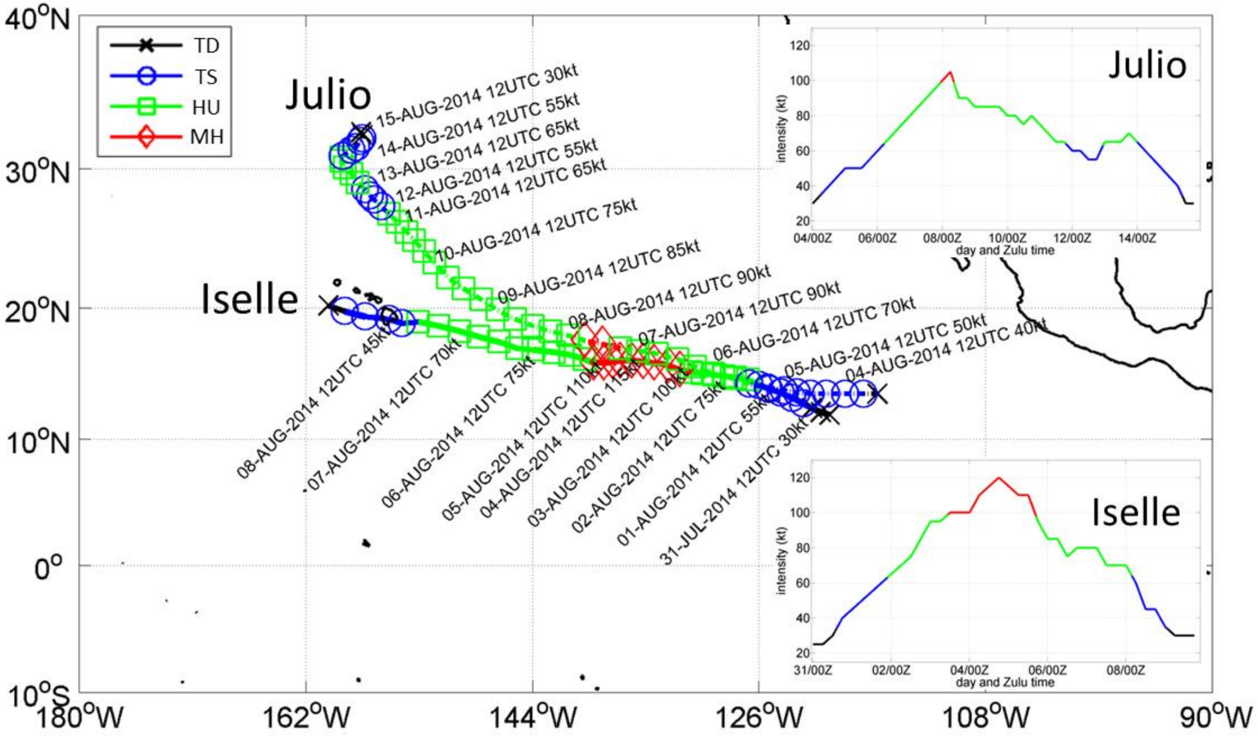


Data and methods

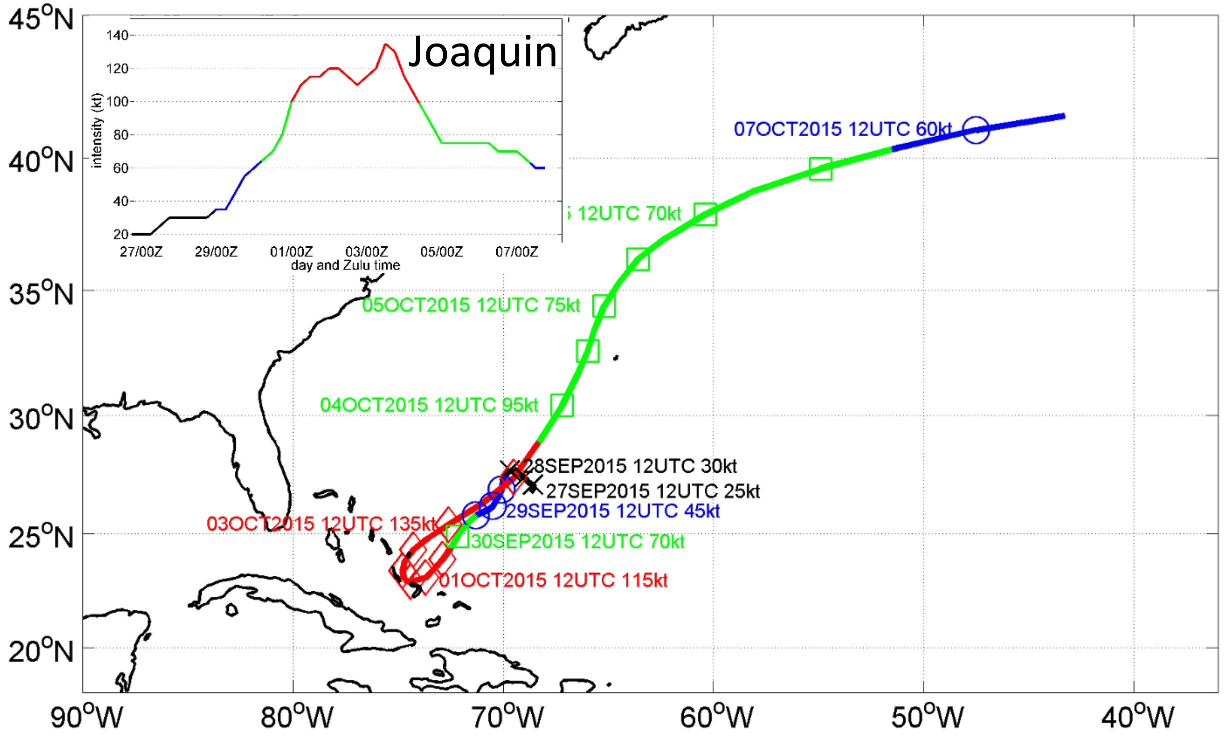
- Determined subjectively storm centers from NAVGEM analyses at each pressure level and 6-hr time
  - Examined wind field on each pressure surface to determine storm center at that level
- Created Hovmöller diagrams to depict radial and azimuthal evolution of outflow and inertial stability in time
  - Converted u, v components to radial u_r and azimuthal u_ϑ components
  - Averaged outflow (positive u_r) and inertial stability both radially and azimuthally
  - Storm center defined using 850-mb level
- Focused on outflow in the inner part of the TC
  - Examined winds 6° (~ 600 km) from storm center
- Calculated inertial stability (I^2) as $I^2 = (\zeta + f_0)\left(f_0 + \frac{2V_\theta}{r}\right)$

Tracks and intensities of Iselle and Julio (2014) and Joaquin (2015)

Iselle and Julio



Joaquin

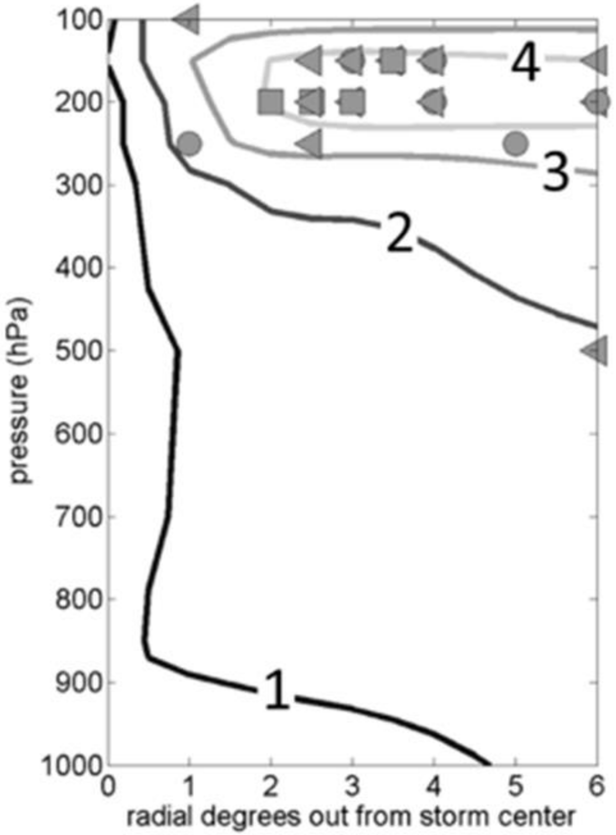


Result #1: vertical and radial distributions of outflow

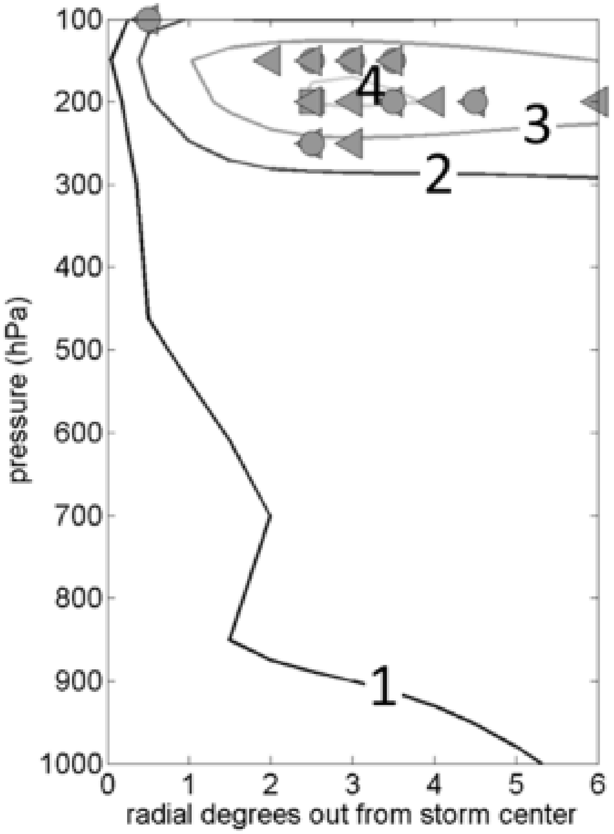
<u>For all 3 storms</u>:

1. Greatest outflow located between 150 and 200 hPa
2. Greatest outflow between 2 and 4 degrees out from storm center
3. Greatest outflow insensitive to storm intensity

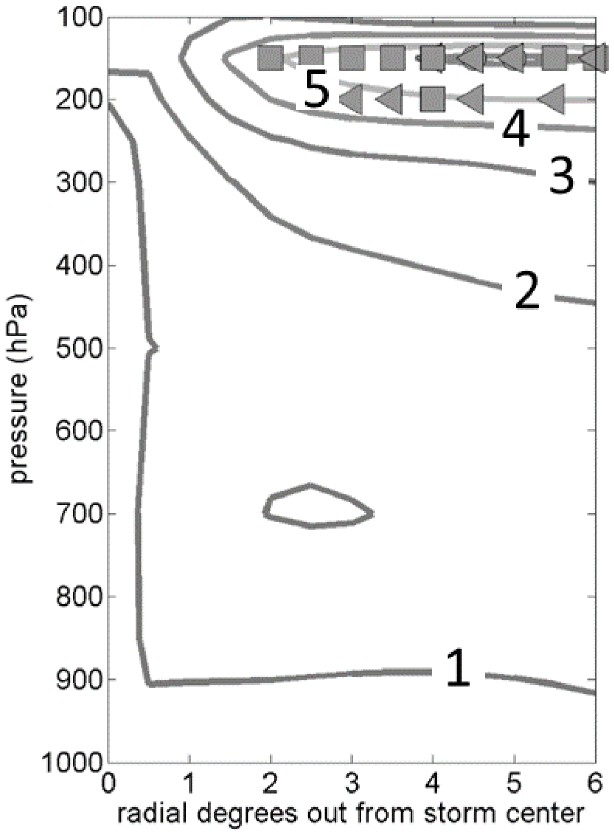
Iselle



Julio

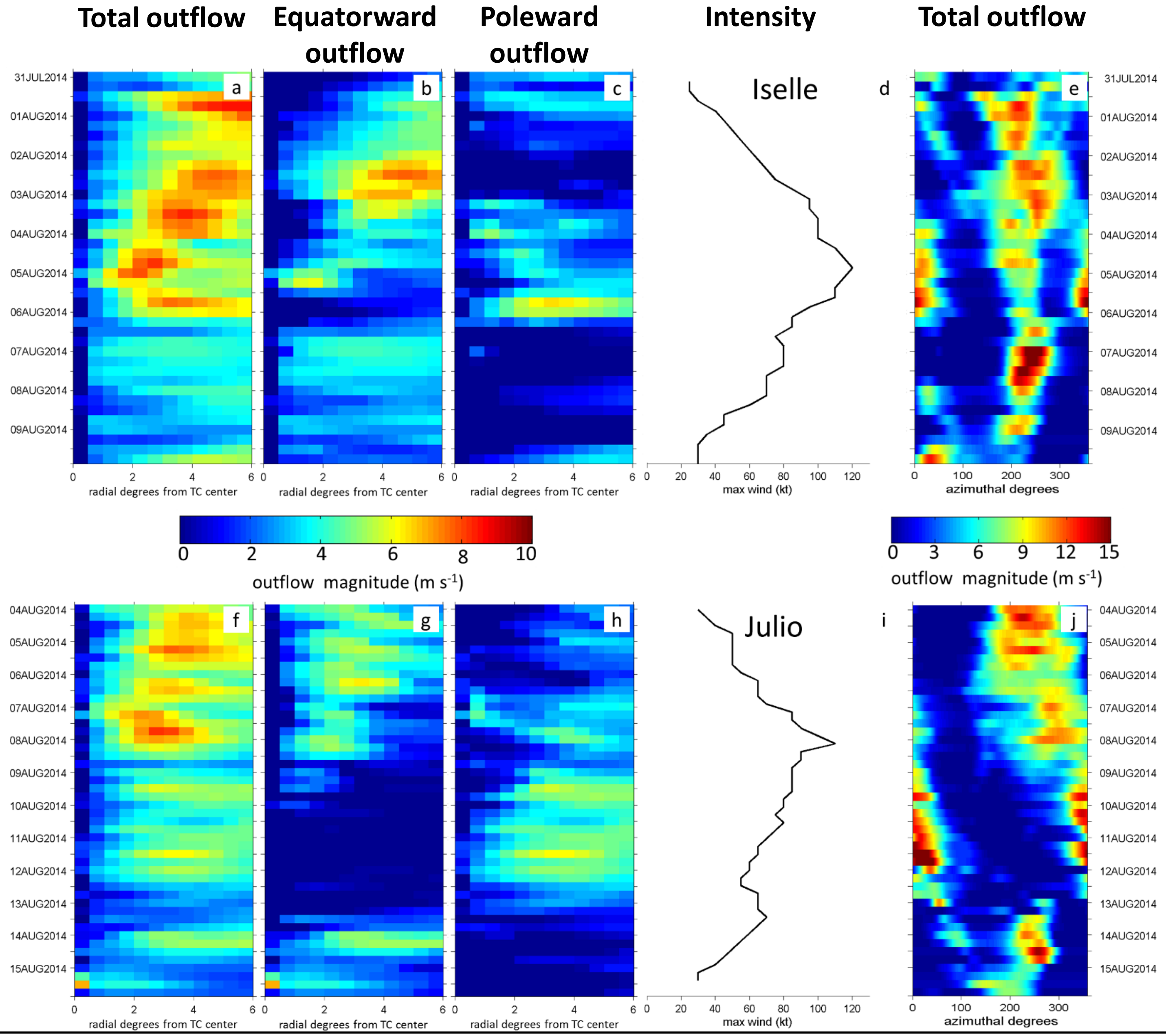


Joaquin



Result #2: outflow evolution in time

1. Inward progression of stronger outflow toward storm center during intensification
    - Seen in both Iselle and Julio
2. Stronger outflow magnitudes during strengthening. Weaker outflow magnitudes during weakening.
3. Outflow direction tied to synoptic-scale features
    - Equatorward-directed outflow when TCs were located to the east of synoptic-scale anticyclones
    - Poleward-directed outflow when TCs were located to the southeast of synoptic-scale troughs



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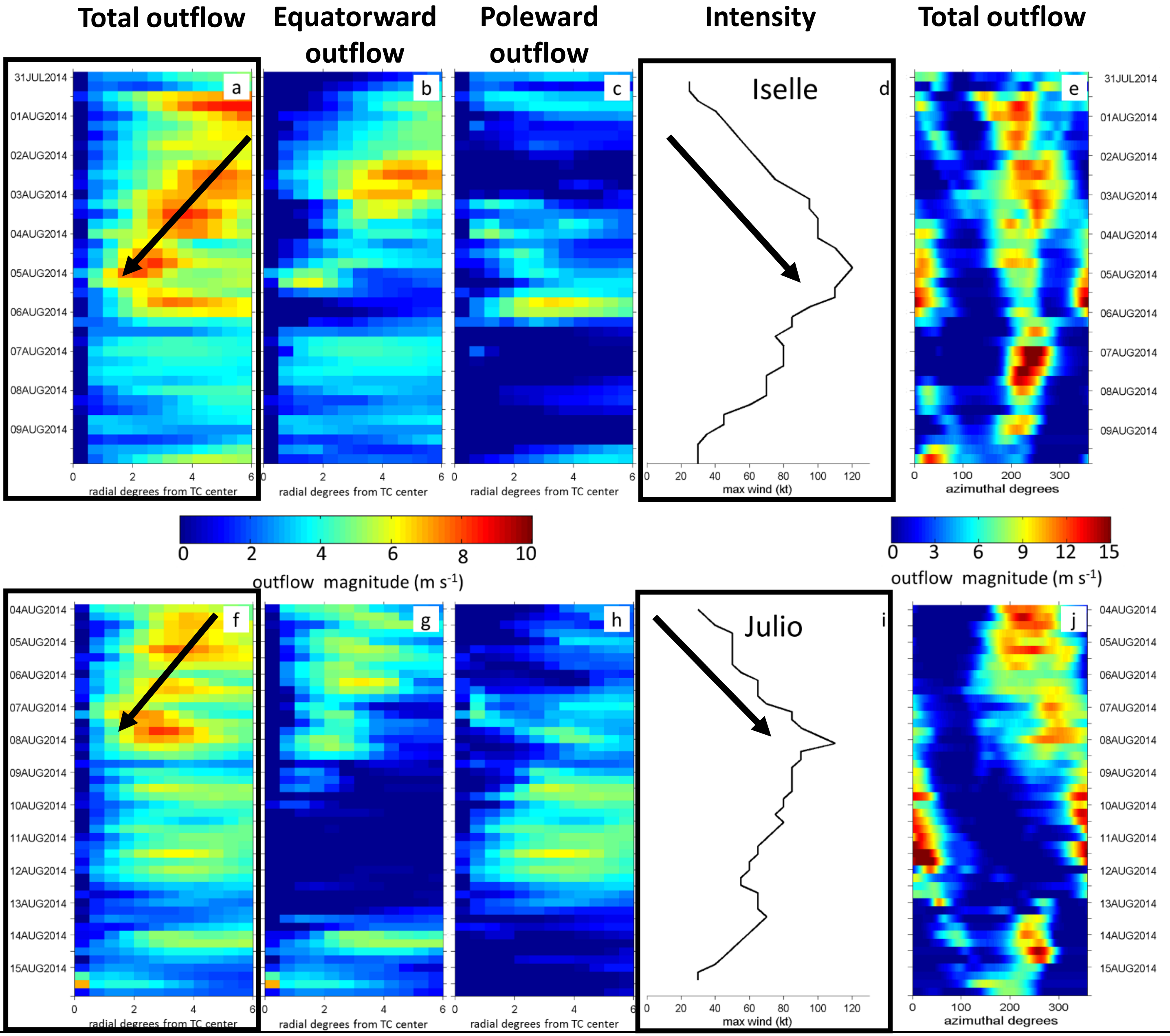

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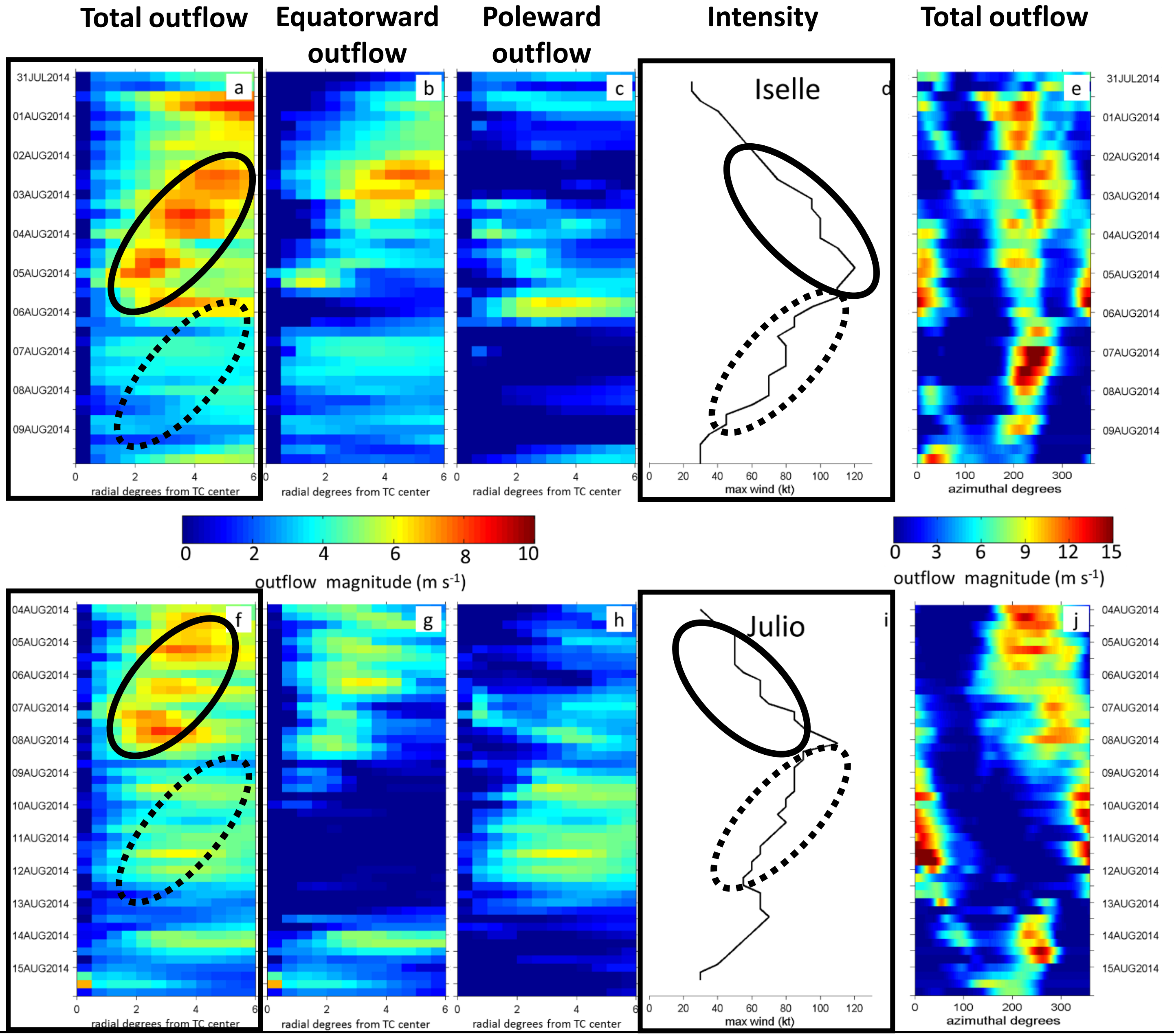

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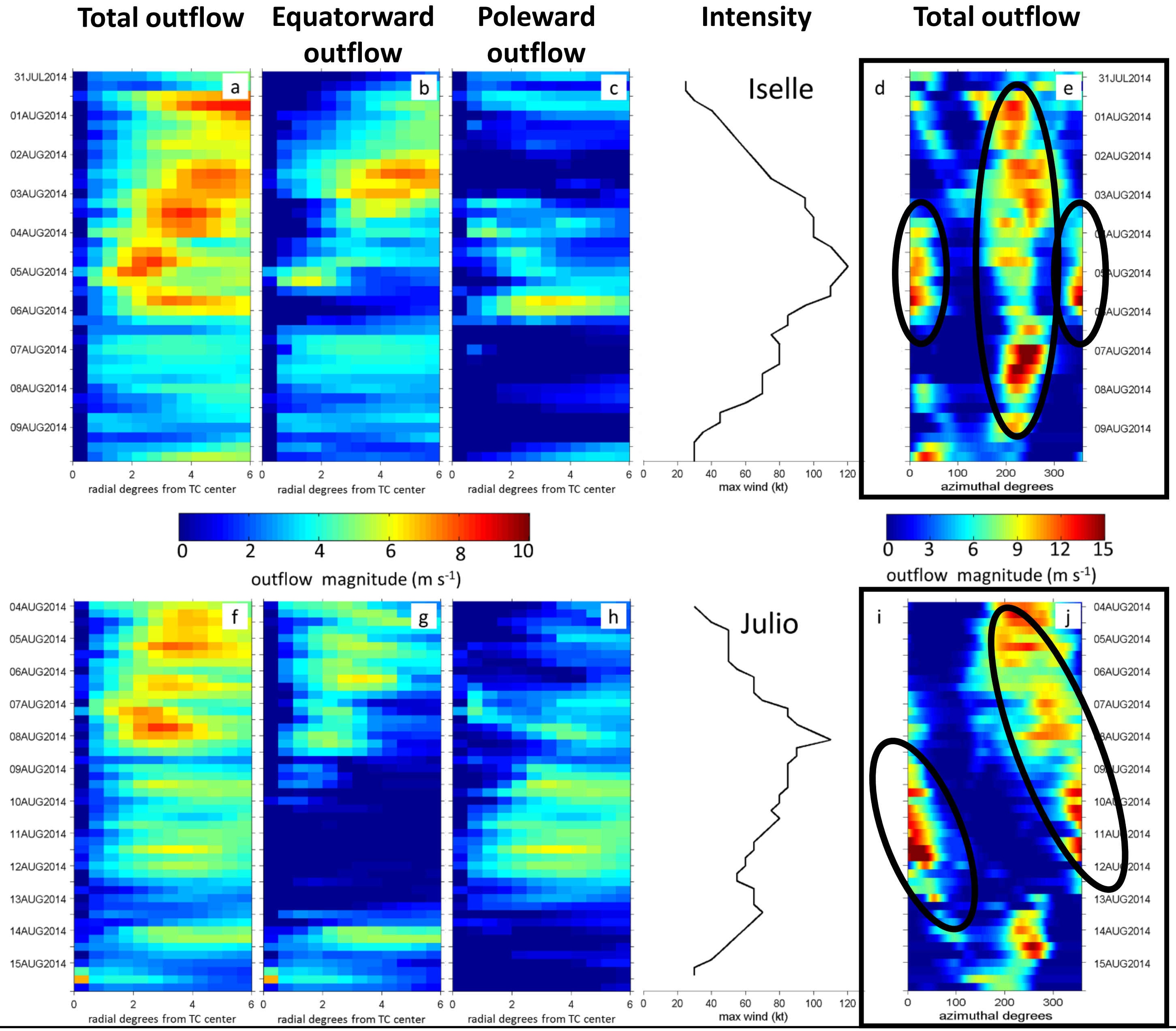
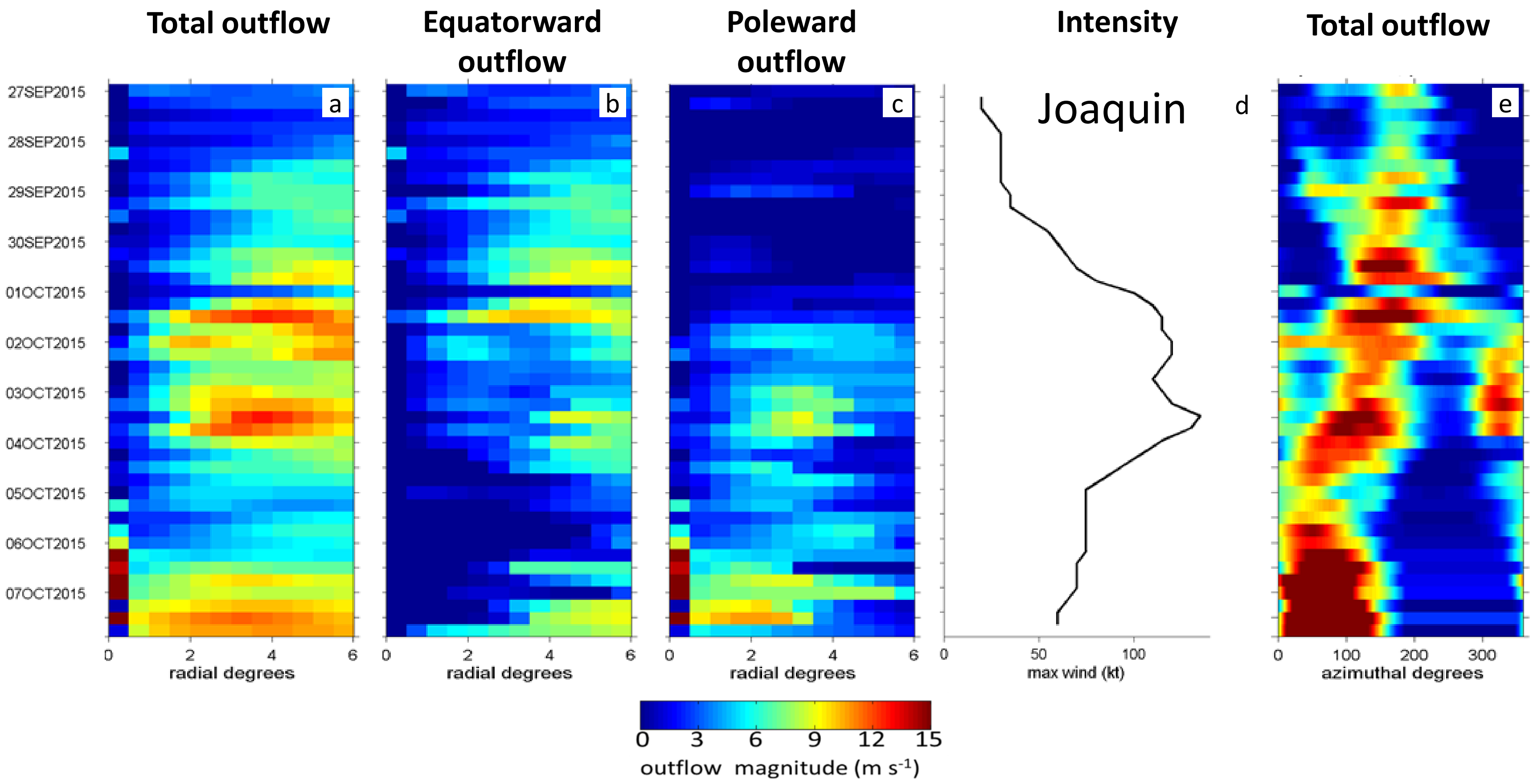


Result #2 (continued): Outflow evolution in time

1. Inward progression of outflow toward storm center during intensification
    - Also seen in both Iselle and Julio
2. Stronger outflow magnitudes during strengthening. Weaker outflow magnitudes during weakening.
    - Exception: strong outflow noted during ET
3. Outflow direction connected to synoptic-scale features



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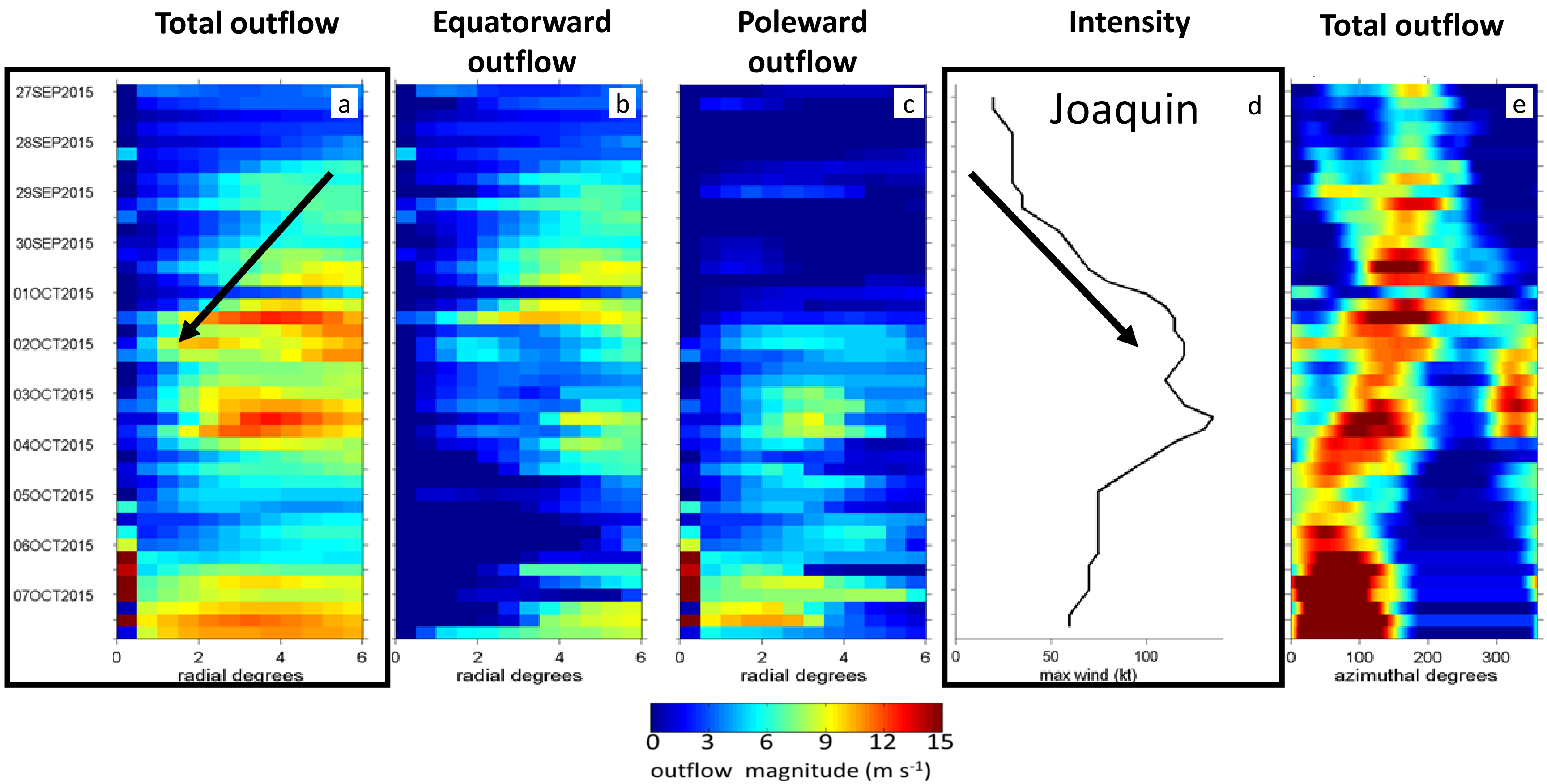

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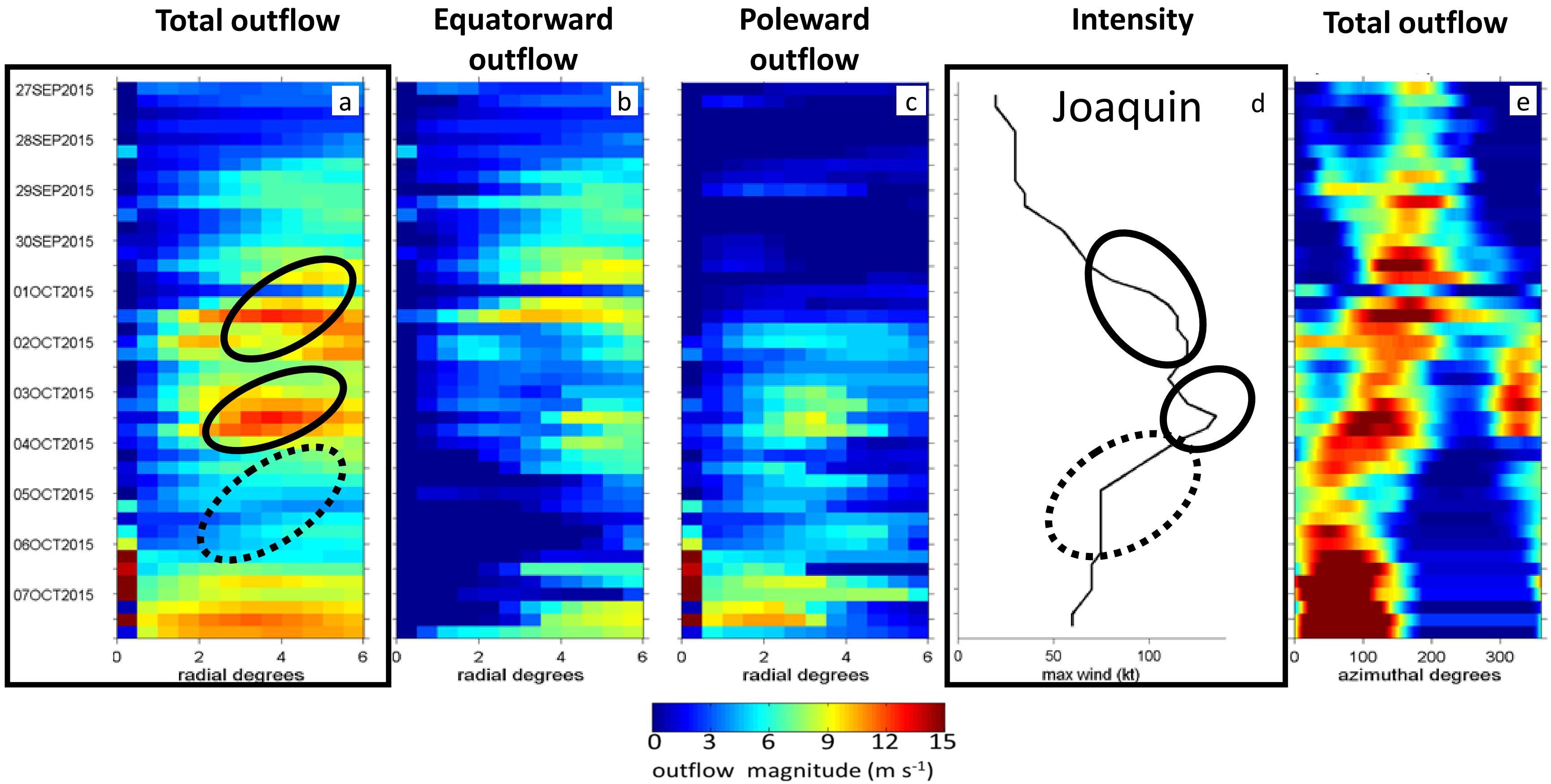

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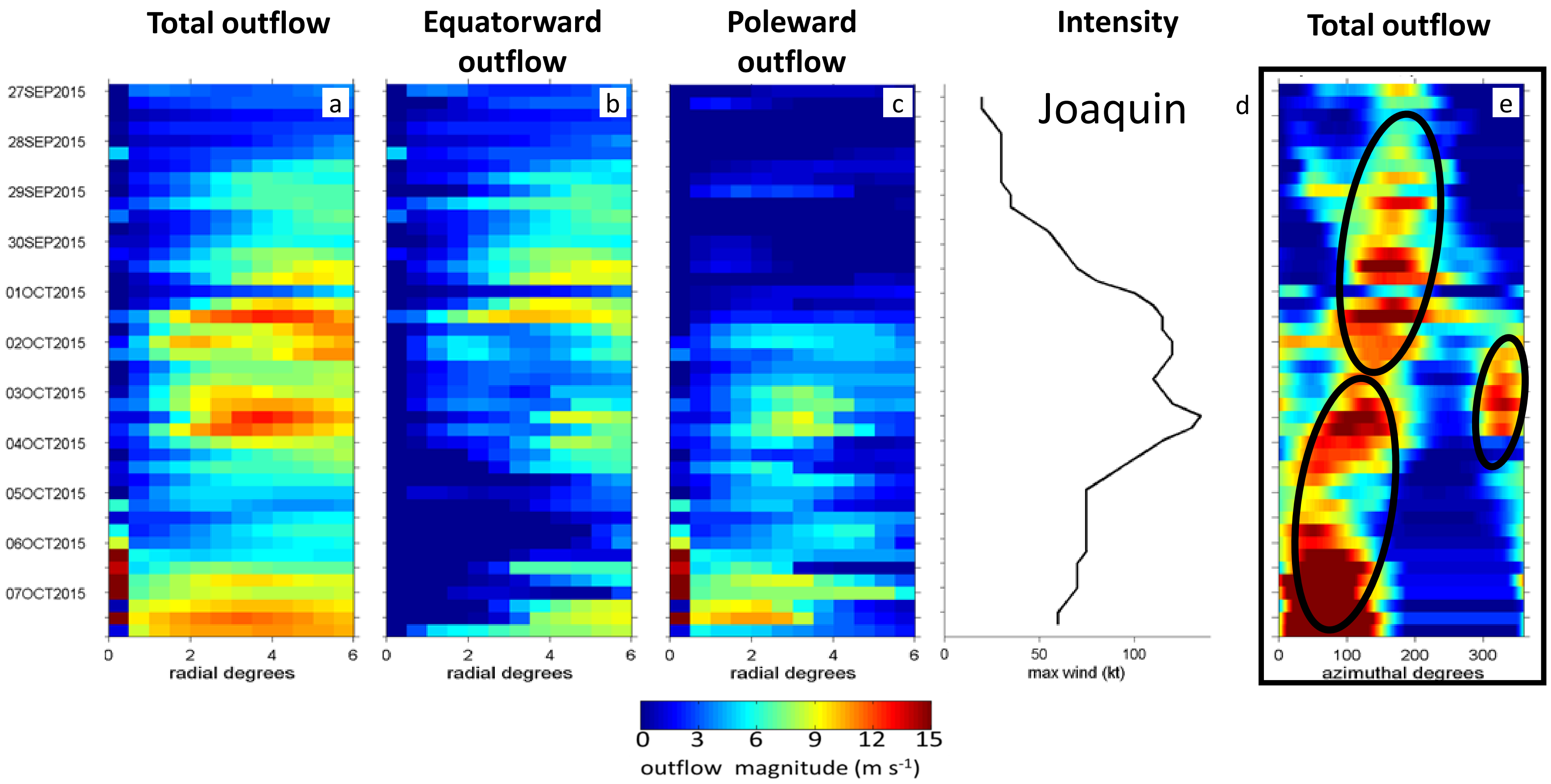
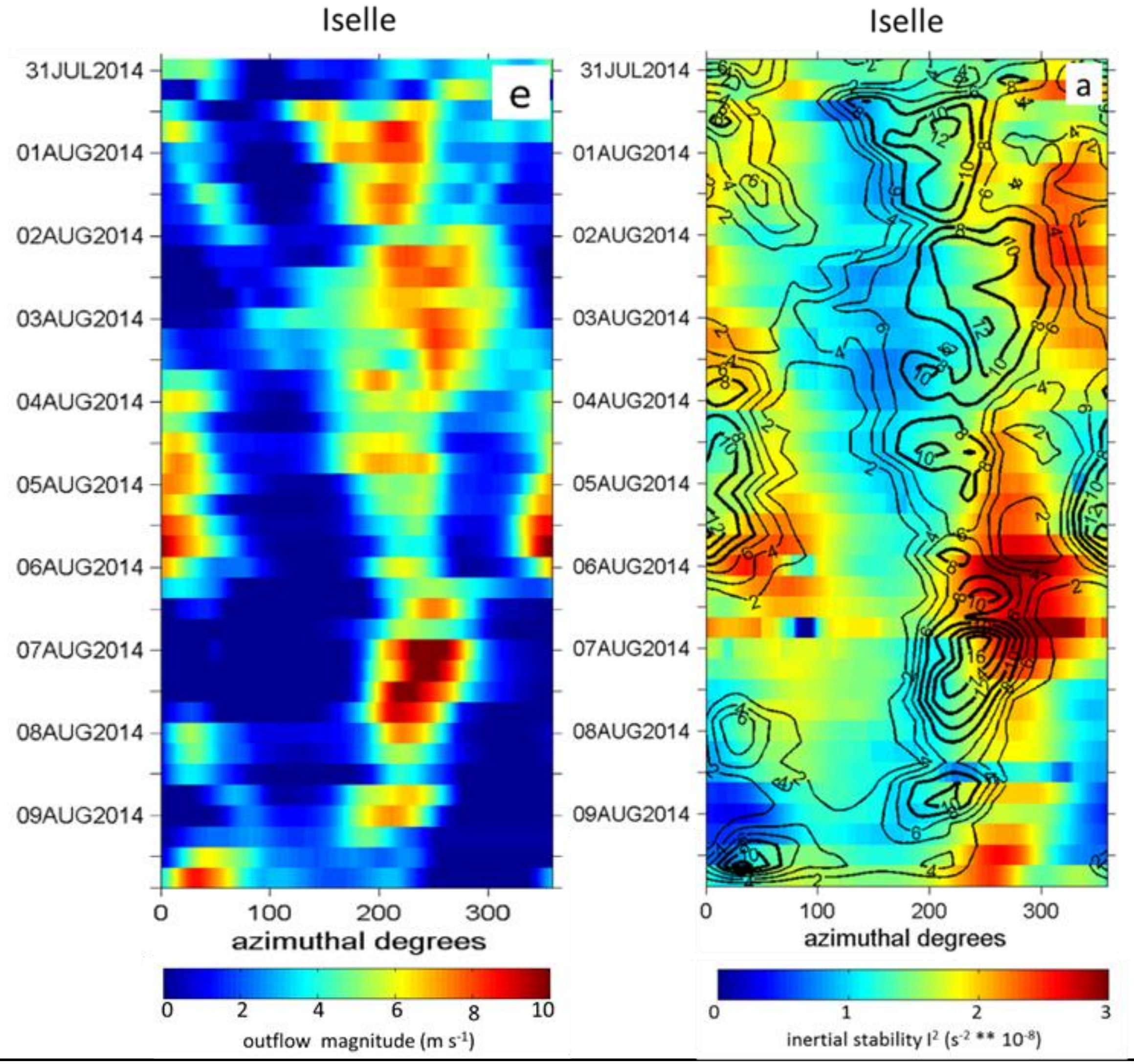


Result #3: Inertial stability $I^2=(\zeta+f_0)\left(f_0+\frac{2V_\theta}{r}\right)$ and outflow

- Quick sidebar on I^2 Hovmöller: colors represent inertial stability (s^{-2}). Reds are more stable (larger I^2); blues less stable (smaller I^2).
- Black contours represent outflow (m s^{-1}).
- Both outflow and inertial stability are radially averaged (out to 6 lat/lon degrees from TC center) at each azimuth



Inertial stability is **colored**

Outflow is in **black** contours

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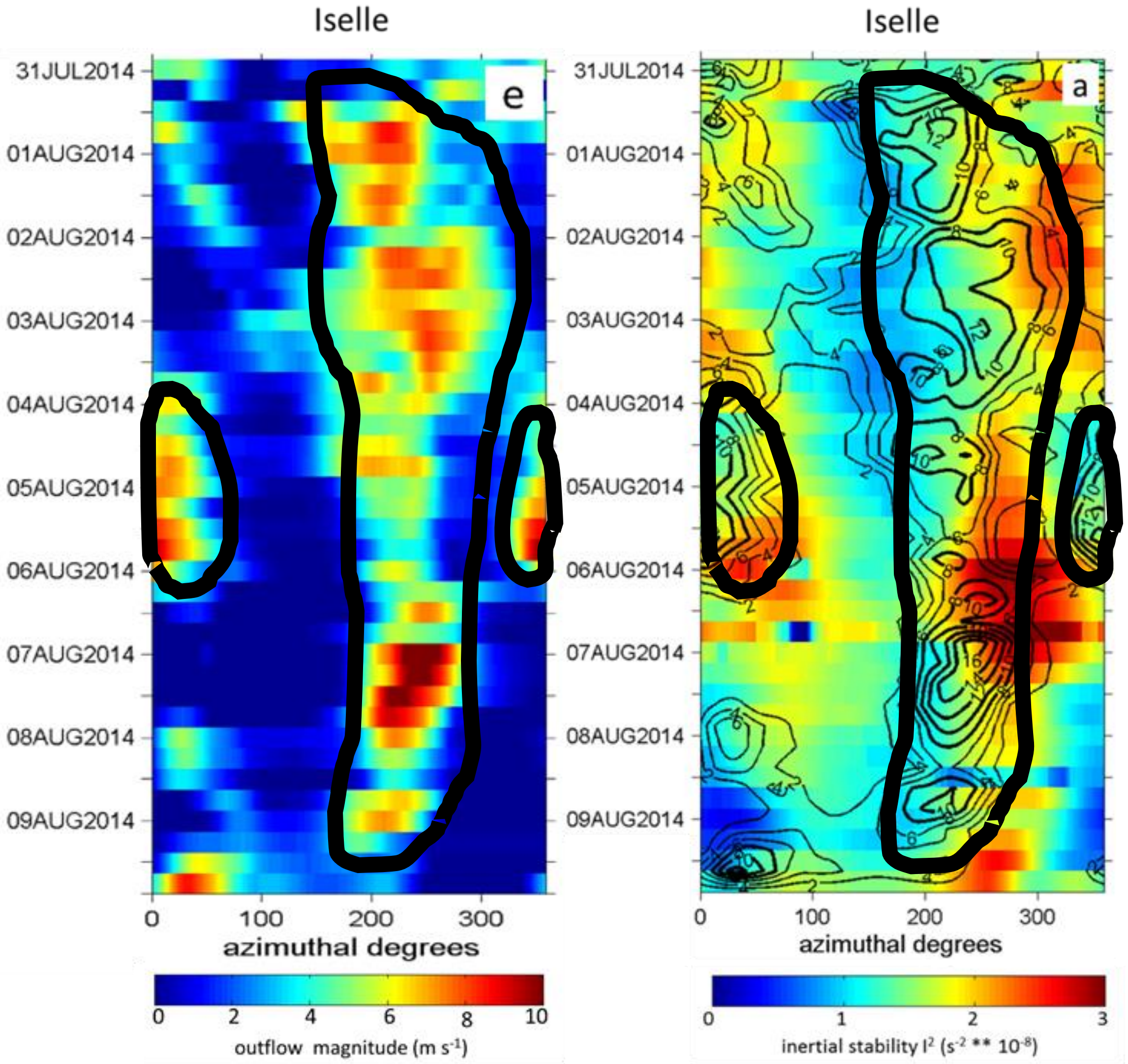

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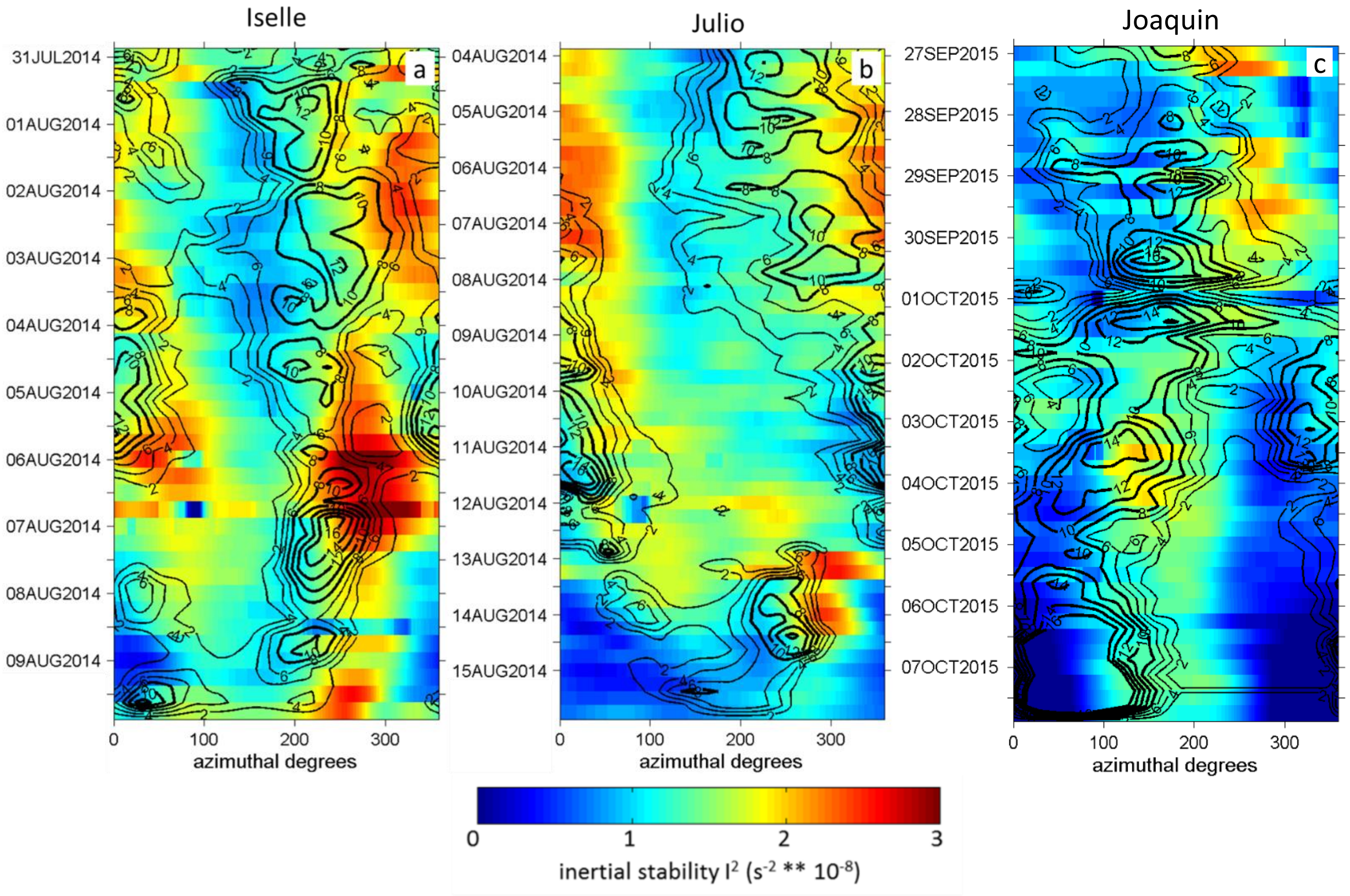
Outflow is in **black** contours

Result #3: Inertial stability $I^2 = (\zeta + f_0)\left(f_0 + \frac{2V_\theta}{r}\right)$ and outflow

1. Outflow (black contours) not located in regions of lowest I^2, but instead between regions of lowest and highest I^2
2. Outflow was bounded by regions of lowest values of inertial stability counterclockwise from the maximum outflow azimuth
3. Outflow was bounded by regions of highest values of inertial stability clockwise from the maximum outflow azimuth
    - Pattern persisted throughout the life cycles of all three storms
    - Seen independent of intensity, environmental flow, and the number and direction of outflow channels present



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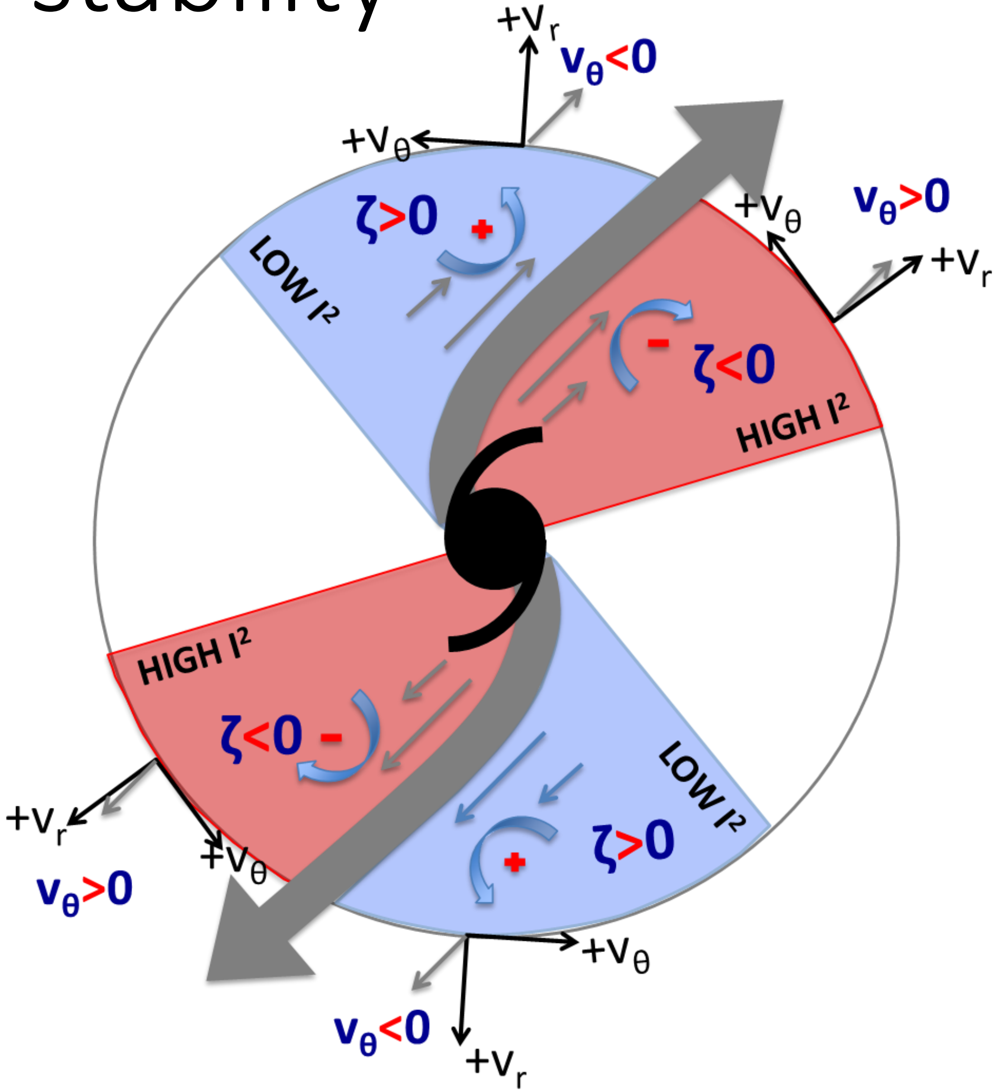
Result #3: more on inertial stability and outflow

$$I^2 = (\zeta + f_0)\left(f_0 + \frac{2V_\theta}{r}\right)$$

- Lowest I^2 was located on the cyclonic (positive) relative vorticity side of the outflow
- Highest I^2 was located on the anticyclonic (negative) relative vorticity side of the outflow
  - This relationship between I^2 and relative vorticity occurred mathematically because the sign of v_θ was consistently opposite of relative vorticity.
- This result held for both equatorward and poleward outflow, for different positions of the TC relative to synoptic-scale environmental flow, and for one and two outflow channels



Result #3: Inertial stability and outflow

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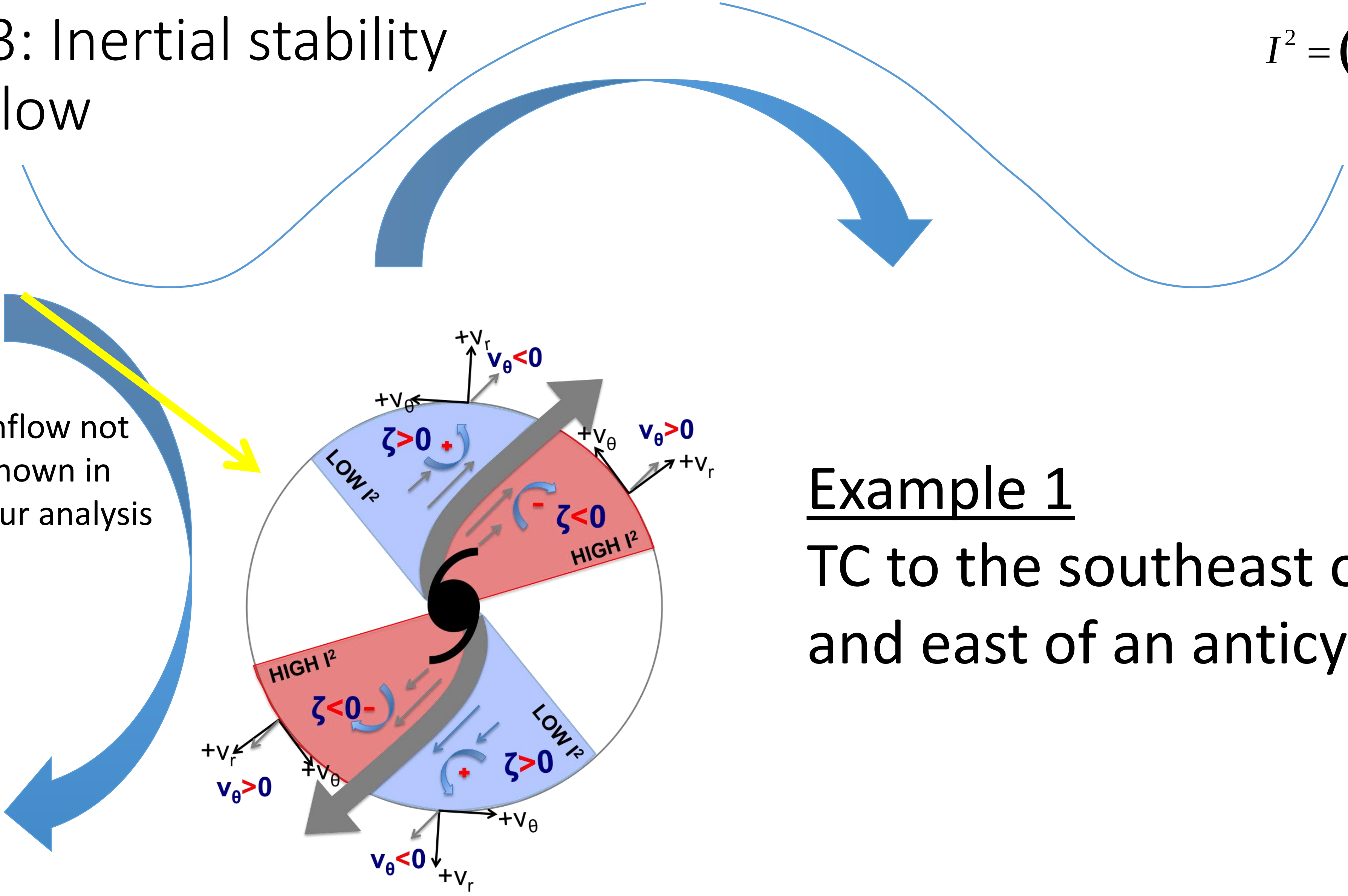

Inflow not shown in our analysis

<u>Example 1</u>

TC to the southeast of a trough and east of an anticyclone

Result #3: Inertial stability and outflow

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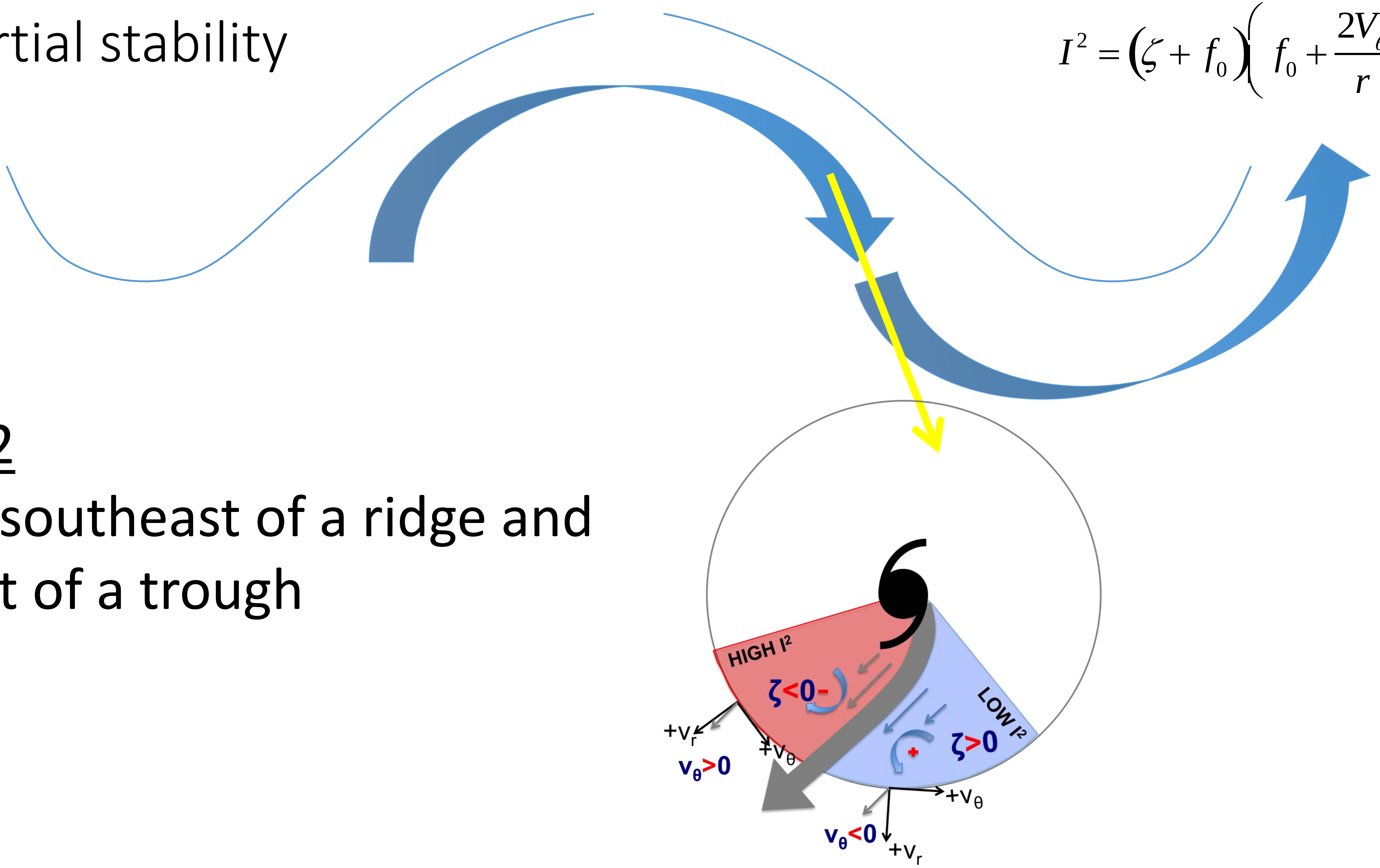

Example 2

TC to the southeast of a ridge and southwest of a trough

Result #3: Inertial stability and outflow

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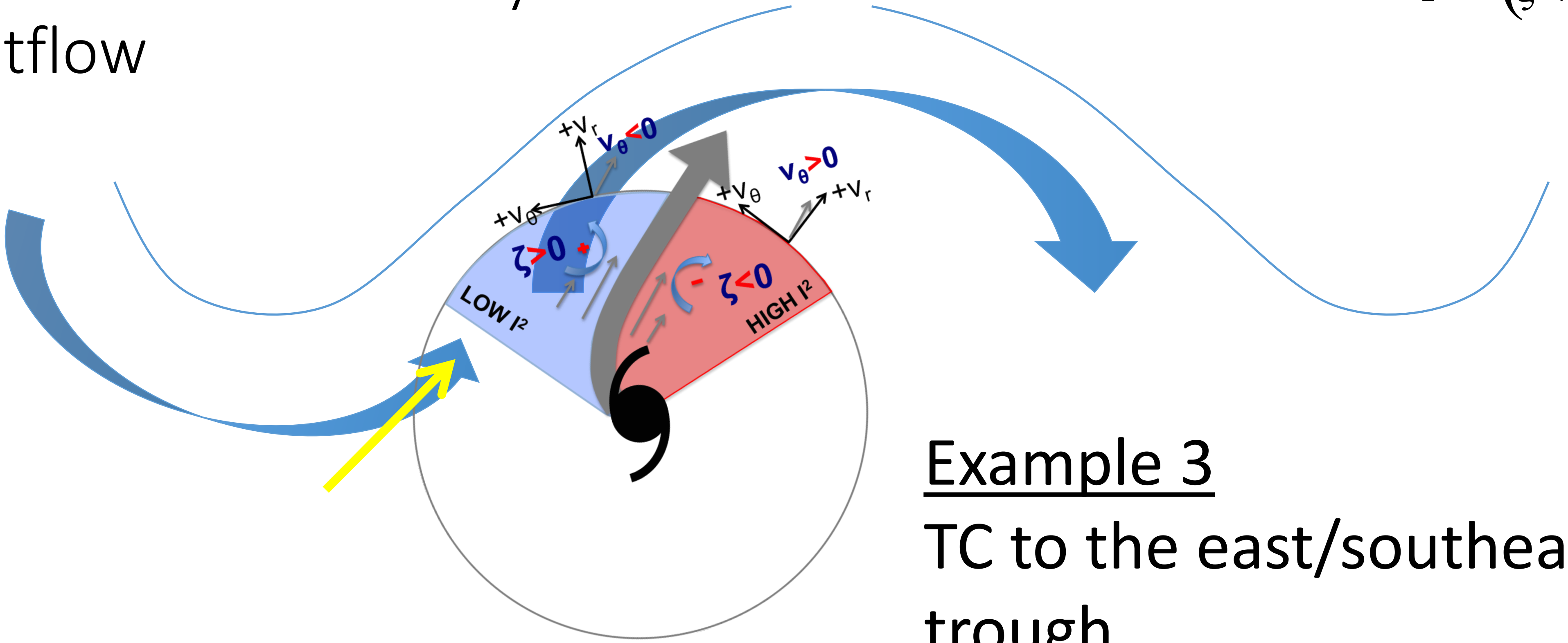
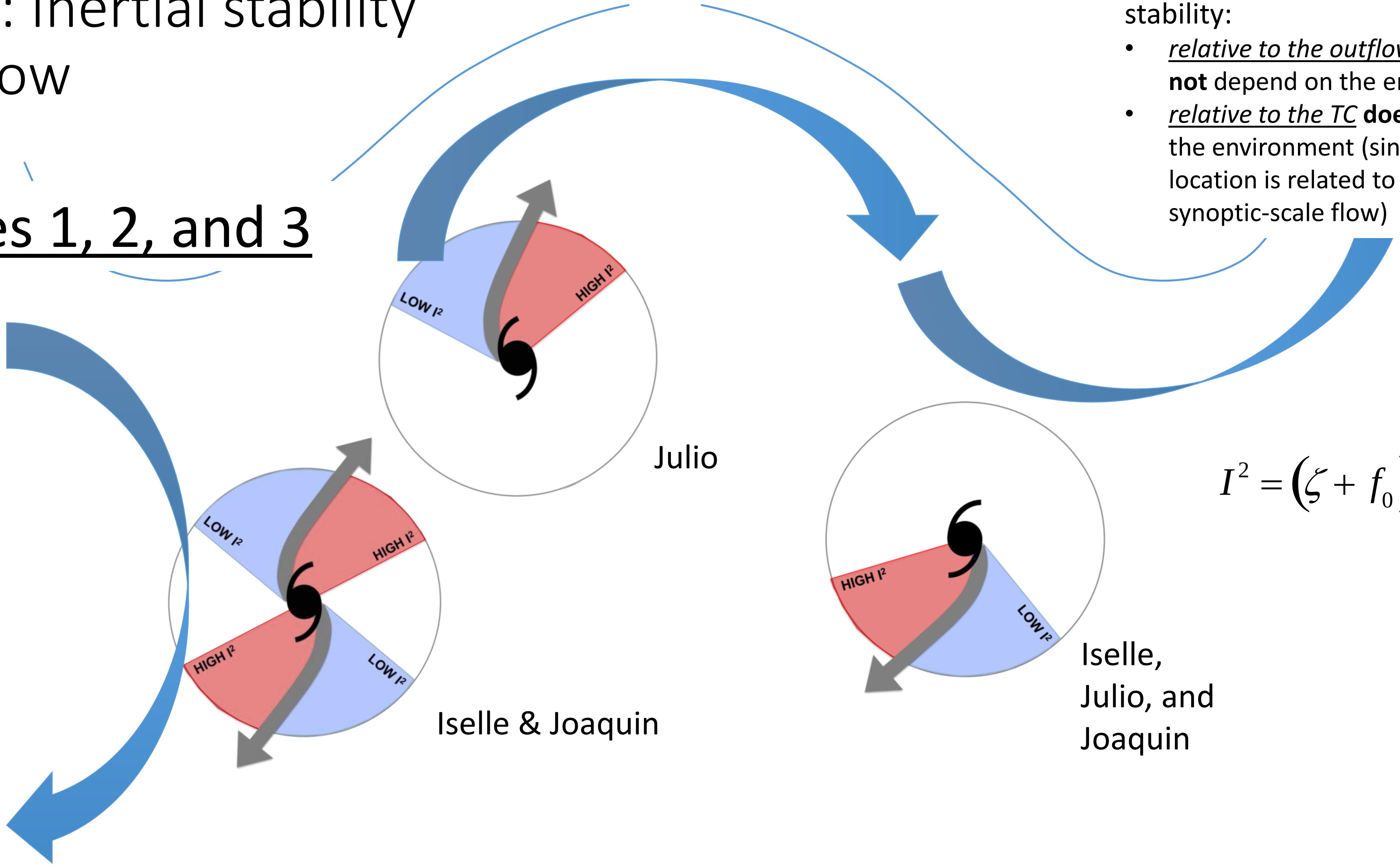


Example 3

TC to the east/southeast of a trough

Result #3: Inertial stability and outflow

Examples 1, 2, and 3



Azimuthal orientation of inertial stability:

- *relative to the outflow* **does not** depend on the environment
- *relative to the TC* **does** depend on the environment (since outflow location is related to surrounding synoptic-scale flow)

$$I^2 = (\zeta + f_0)\left(f_0 + \frac{2V_\theta}{r}\right)$$

Conclusions & future work

$$I^2 = (\zeta + f_0)\left(f_0 + \frac{2V_\theta}{r}\right)$$

- Outflow is related to environmental flow
  - Outflow channel orientation is consistent with location of troughs and ridges in the environmental flow
- Outflow is connected to TC intensity
  - Max outflow moves closer to the center of the TC as the storm intensifies and is closest to the TC center at max intensity
- Outflow is related to inertial stability
  - Outflow channels were bound by lower (higher) values of inertial stability counterclockwise (clockwise) from the maximum outflow azimuth
- Outflow links inertial stability and the environment
  - The azimuthal orientation of inertial stability:
    - *relative to the outflow* **does not** depend on the environment
    - *relative to the TC* **does** depend on the environment (since outflow location is related to the surrounding synoptic-scale flow)
- Future work:
  - Further investigate relationships between the TC and the environment, through Eddy Flux Convergence (EFC) and Eddy Kinetic Energy (EKE) analysis
  - Investigate links between outflow and the ocean, including Ocean Heat Content (OHC) and air-sea fluxes (collaboration with M. Bell)