Initial-condition error growth in idealized midlatitude cyclones

Daniel Lloveras, Dale Durran, and Jim Doyle

Predictability involving multi-scale processes and interactions

Background

- What kinds of initial-condition errors lead to midlatitude-cyclone “forecast busts” on 2–4-day timescales? – cyclone + precip significantly change

Background

- What kinds of initial-condition errors lead to midlatitude-cyclone “forecast busts” on 2–4-day timescales? – cyclone + precip significantly change

- Small-scale errors
  - In homogeneous turbulence: upscale error cascade (Lorenz 1969)
  - In midlatitude atmosphere: convective instability → geostrophic adjustment → baroclinic instability (Zhang et al. 2007)

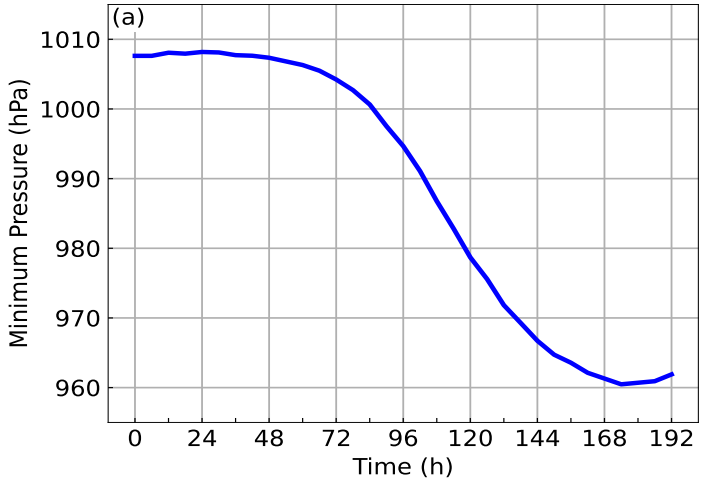
Background

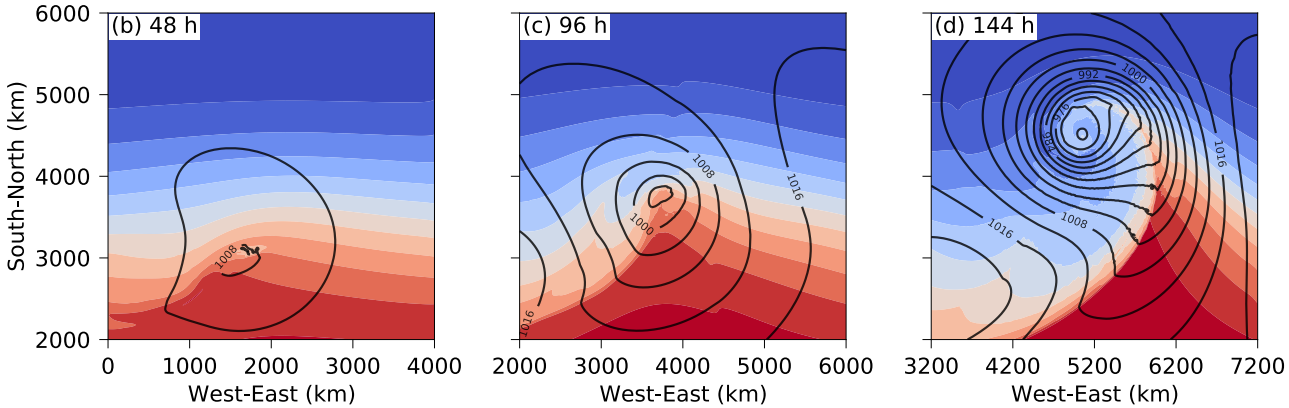
- What kinds of initial-condition errors lead to midlatitude-cyclone “forecast busts” on 2–4-day timescales? – cyclone + precip significantly change
- Small-scale errors
  - In homogeneous turbulence: upscale error cascade (Lorenz 1969)
  - In midlatitude atmosphere: convective instability → geostrophic adjustment → baroclinic instability (Zhang et al. 2007)
- Synoptic-scale errors
  - On average, present-day: more important in midlatitudes (Selz et al. 2022)
  - Midlatitude cyclones? – synoptic disturbances w/ deep convection

Background

- What kinds of initial-condition errors lead to midlatitude-cyclone “forecast busts” on 2–4-day timescales? – cyclone + precip significantly change
- Small-scale errors
  - In homogeneous turbulence: upscale error cascade (Lorenz 1969)
  - In midlatitude atmosphere: convective instability → geostrophic adjustment → baroclinic instability (Zhang et al. 2007)
- Synoptic-scale errors
  - On average, present-day: more important in midlatitudes (Selz et al. 2022)
  - Midlatitude cyclones? – synoptic disturbances w/ deep convection
- Strategy: idealized moist simulations of prototypical midlatitude cyclones
  - “Identical-twin” experiments: perturbed vs. unperturbed runs

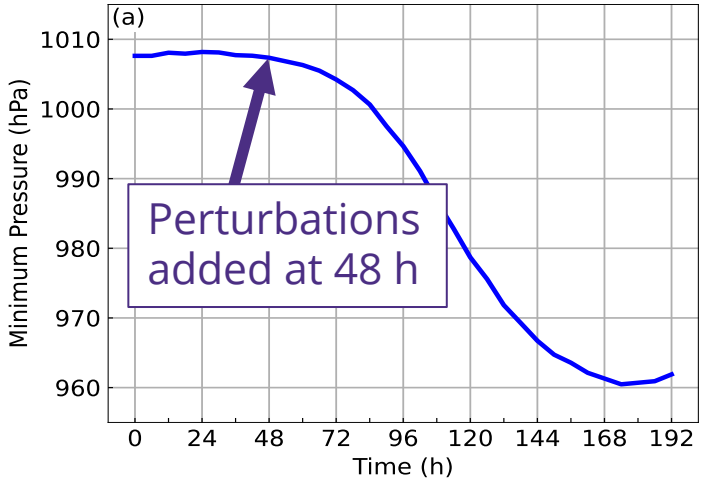
Idealized moist cyclone, Δx = 4 km

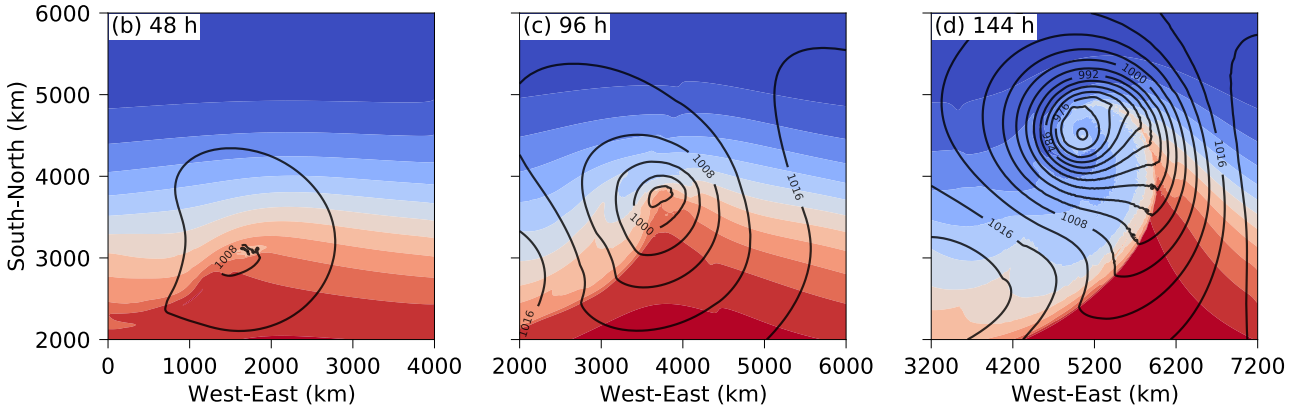




SLP (4 hPa);
Surface temperature (2 K)

Idealized moist cyclone, Δx = 4 km





SLP (4 hPa);
Surface temperature (2 K)

Equal–DTE perturbations

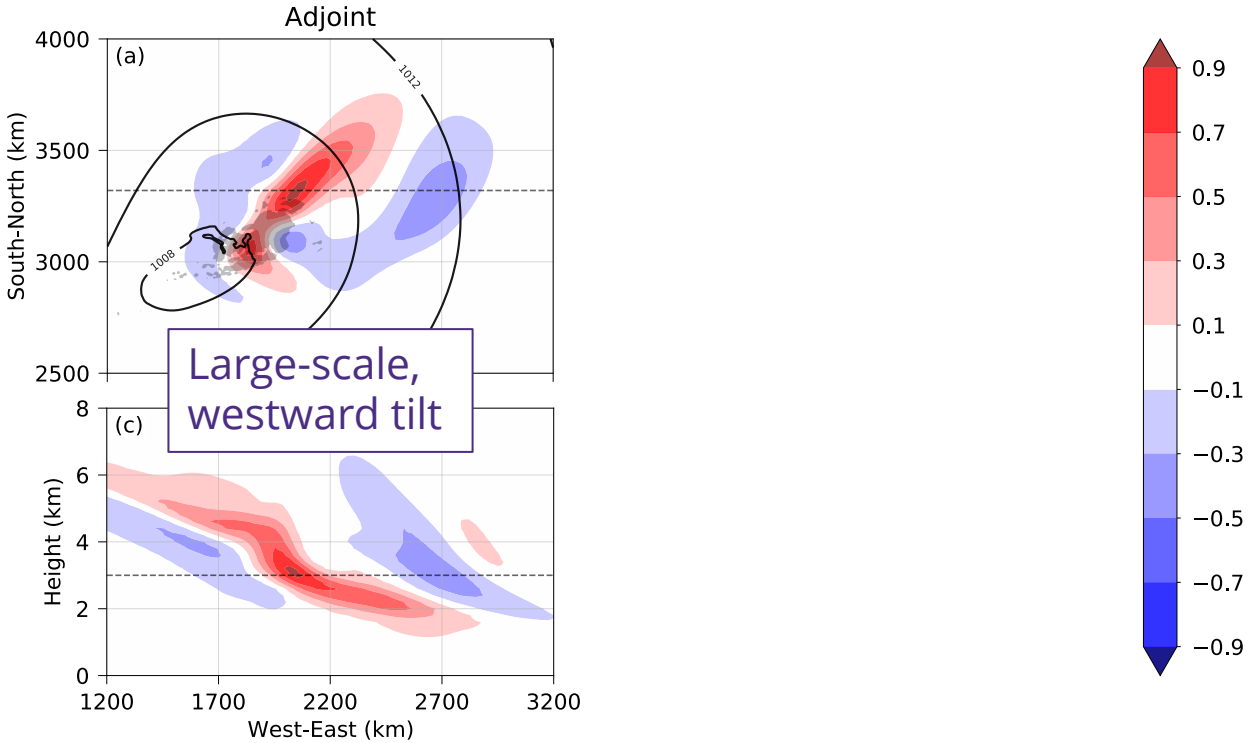
$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

Equal-DTE perturbations

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

Looking down

Looking north



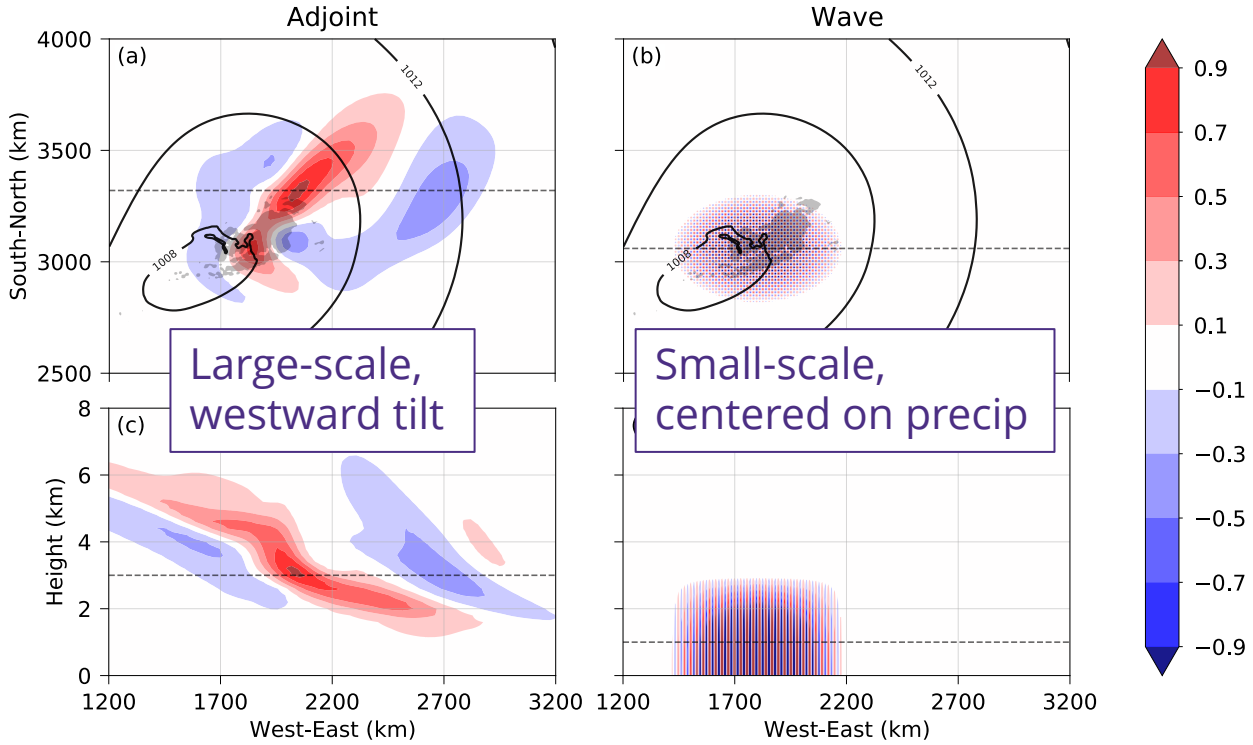
Potential-temperature pert (0.2 K); Ctl reflectivity > 5 dBZ (grey shading); Ctl SLP (4 hPa)

Equal-DTE perturbations

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

Looking down

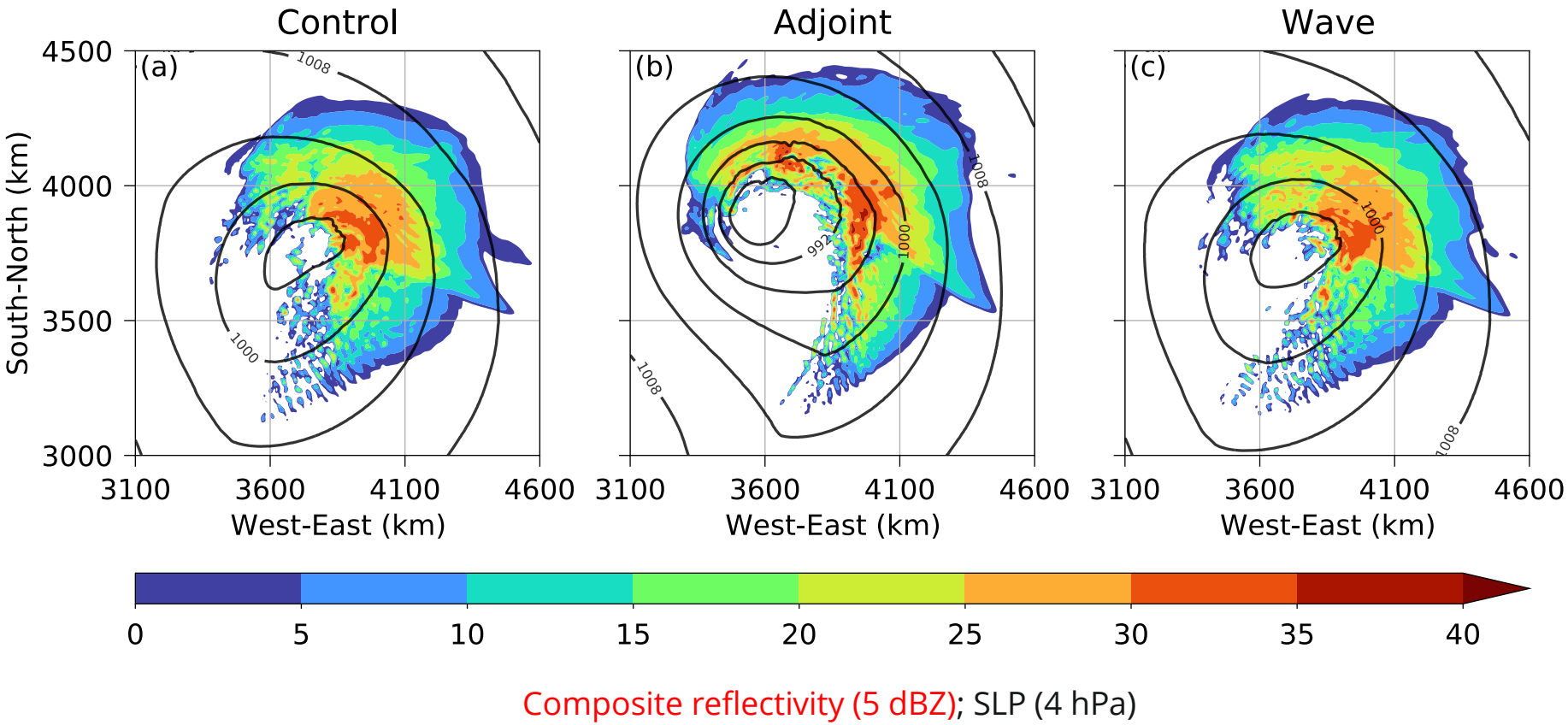
Looking north



Potential-temperature pert (0.2 K); Ctl reflectivity > 5 dBZ (grey shading); Ctl SLP (4 hPa)

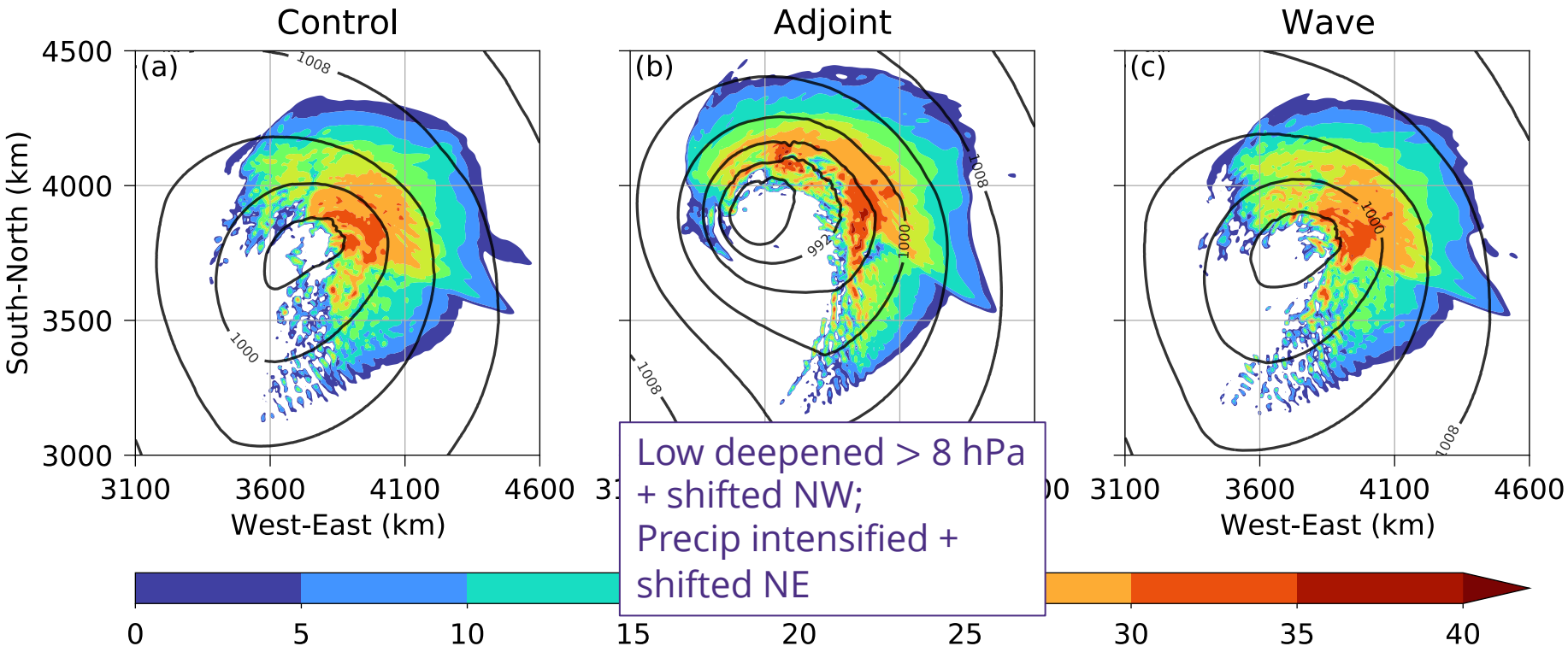
Results at 48-h lead times

Results at 48-h lead times



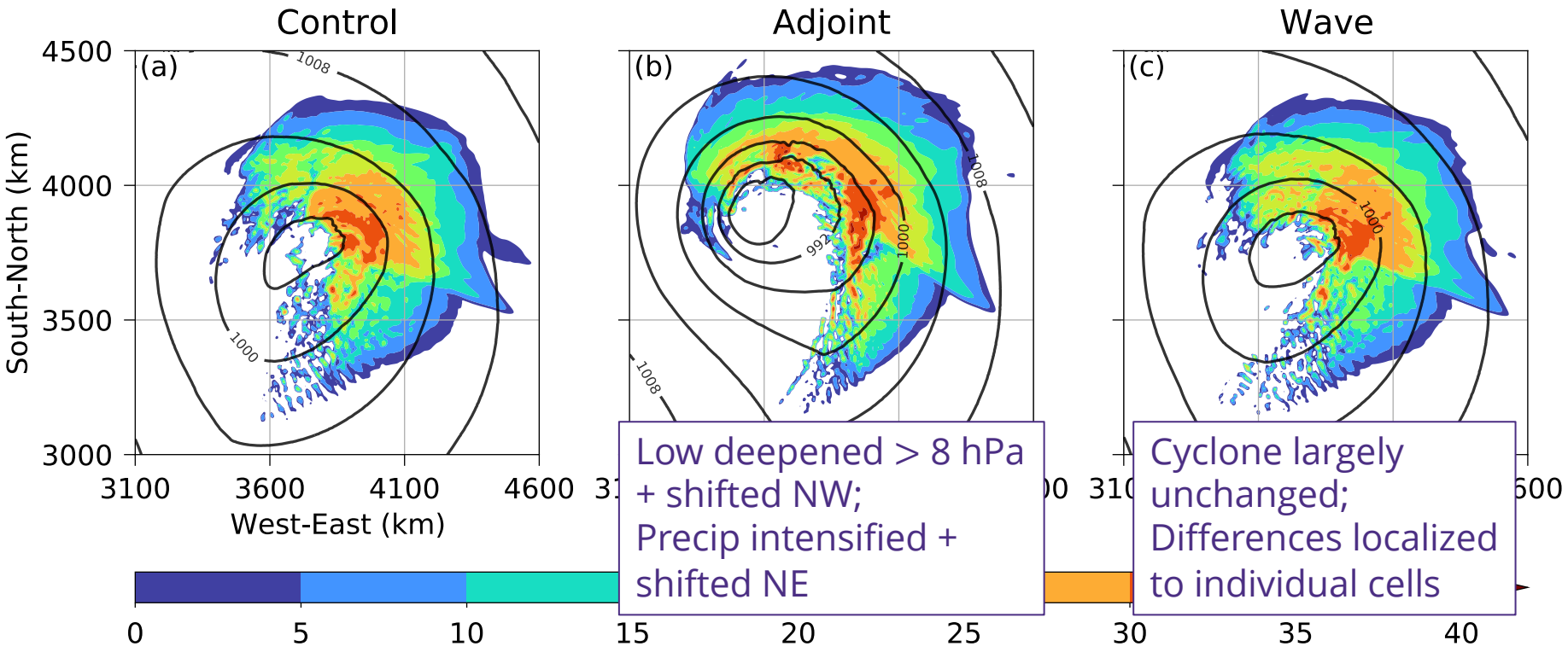
Composite reflectivity (5 dBZ); SLP (4 hPa)

Results at 48-h lead times



Composite reflectivity (5 dBZ); SLP (4 hPa)

Results at 48-h lead times



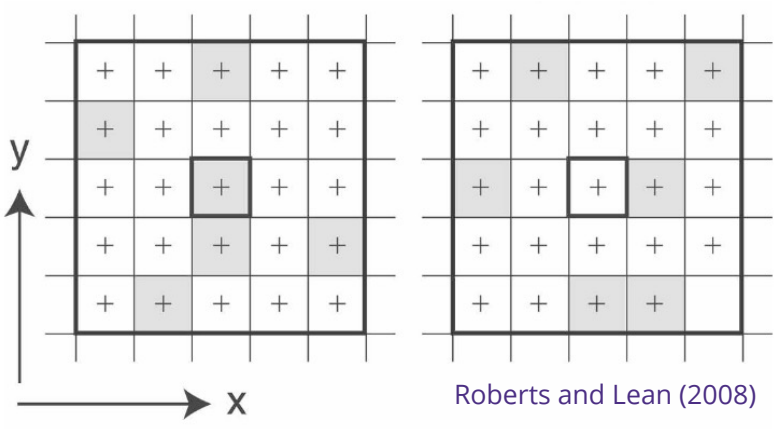
Composite reflectivity (5 dBZ); SLP (4 hPa)

Precipitation changes: fractions skill score (FSS)

Precipitation changes: fractions skill score (FSS)

Shaded = precip > 1 mm/h
Unshaded = precip ≤ 1 mm/h

Control Perturbed

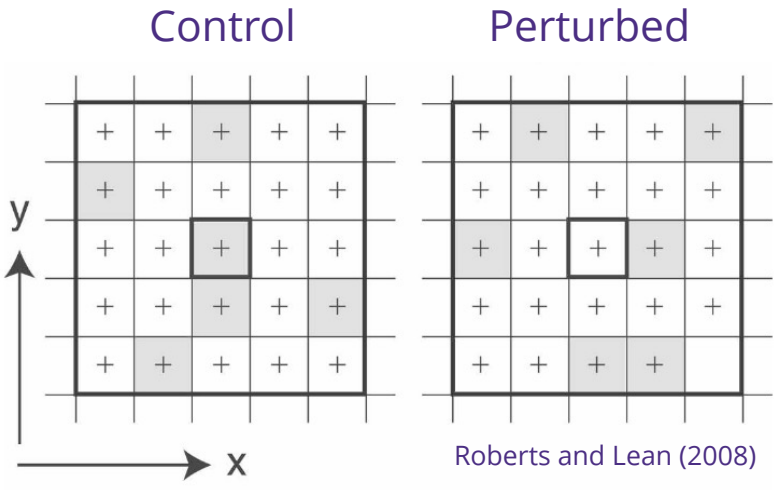


Roberts and Lean (2008)

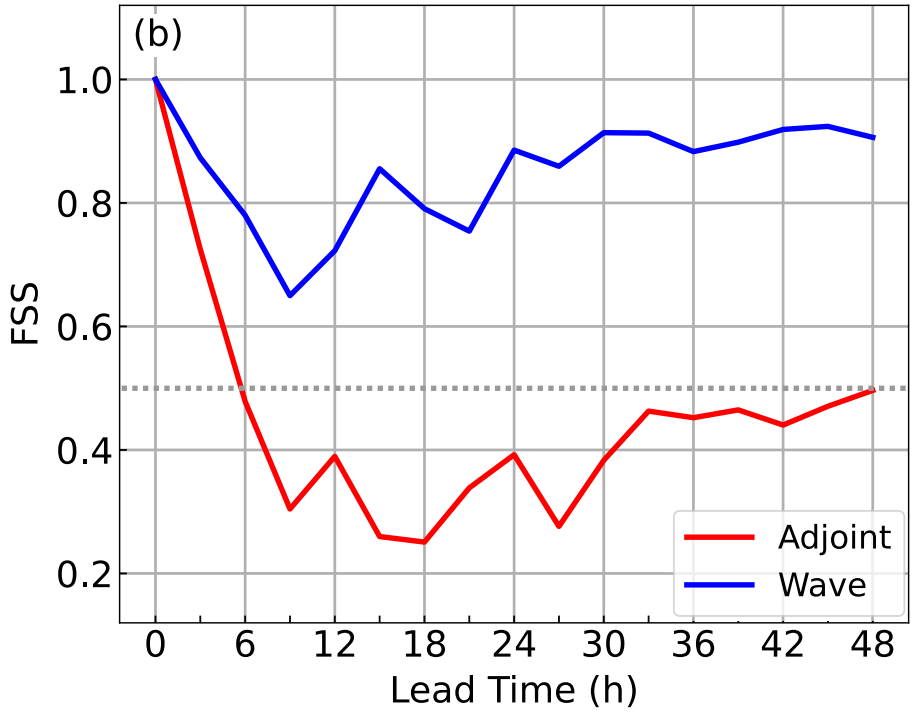
FSS = 1 → ctl + pert neighborhoods have same # of points > 1 mm/h → "perfect" forecast

Precipitation changes: fractions skill score (FSS)

Shaded = precip > 1 mm/h
Unshaded = precip ≤ 1 mm/h

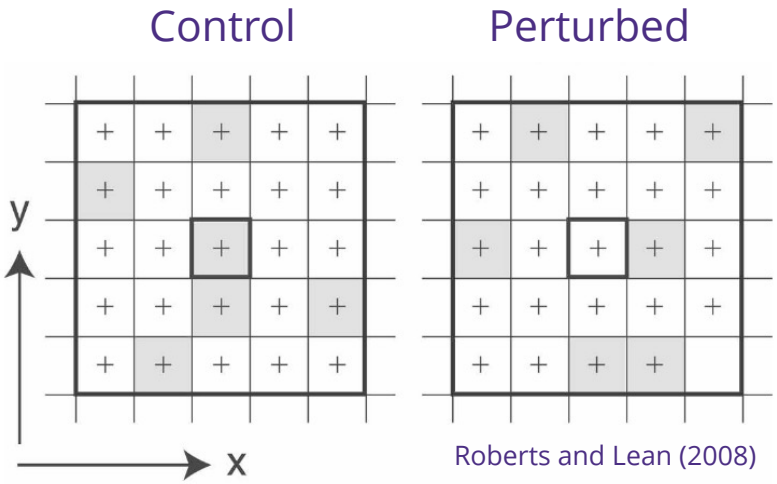


FSS = 1 → ctl + pert neighborhoods have same # of points > 1 mm/h → "perfect" forecast

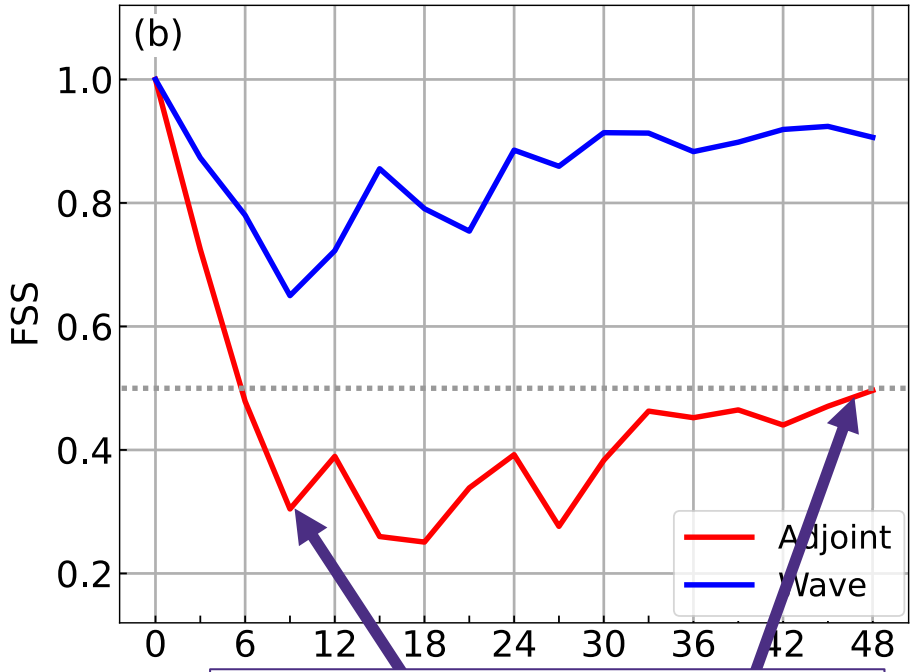


Precipitation changes: fractions skill score (FSS)

Shaded = precip > 1 mm/h
Unshaded = precip ≤ 1 mm/h



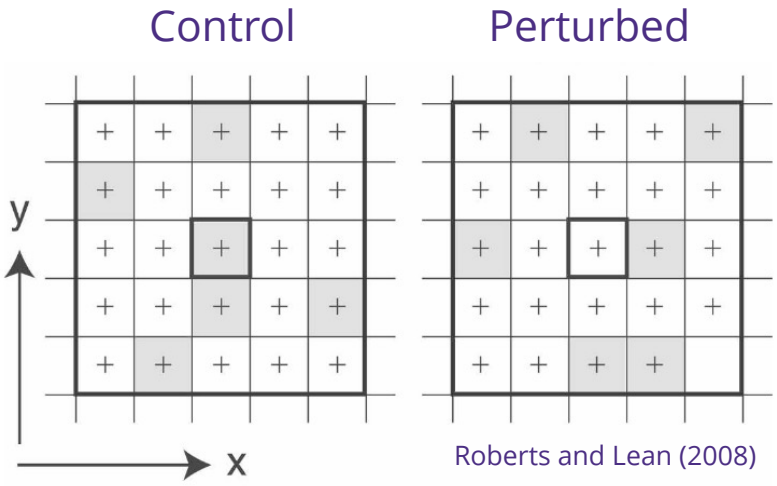
FSS = 1 → ctl + pert neighborhoods have same # of points > 1 mm/h → "perfect" forecast



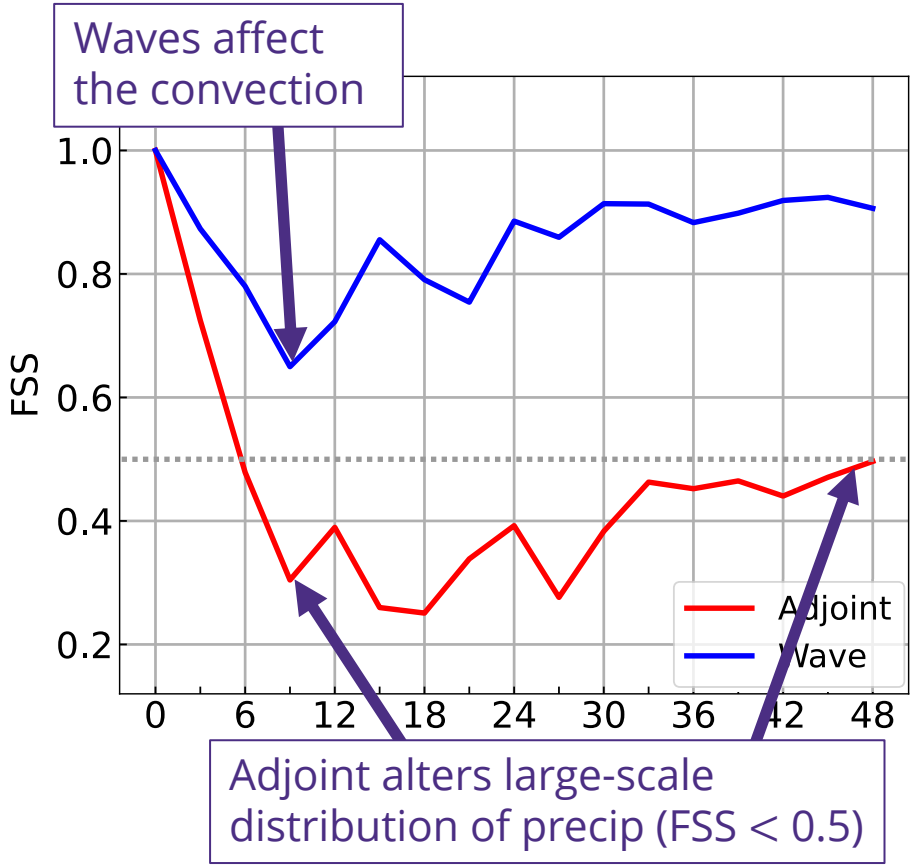
Adjoint alters large-scale distribution of precip (FSS < 0.5)

Precipitation changes: fractions skill score (FSS)

Shaded = precip > 1 mm/h
Unshaded = precip ≤ 1 mm/h

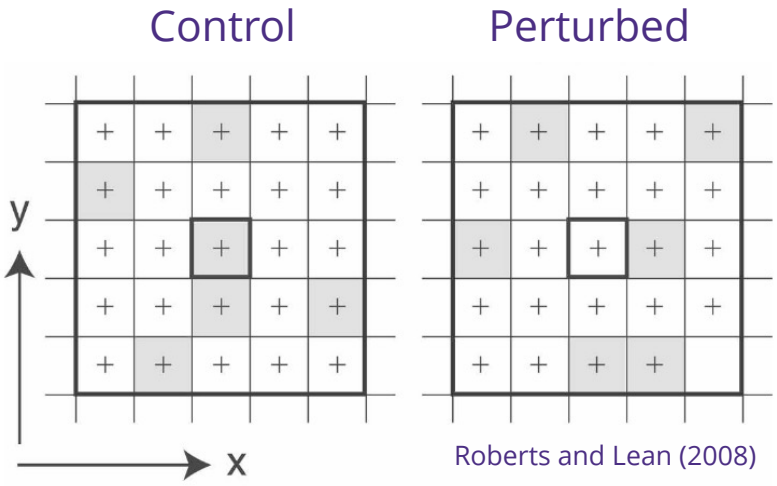


FSS = 1 → ctl + pert neighborhoods have same # of points > 1 mm/h → "perfect" forecast

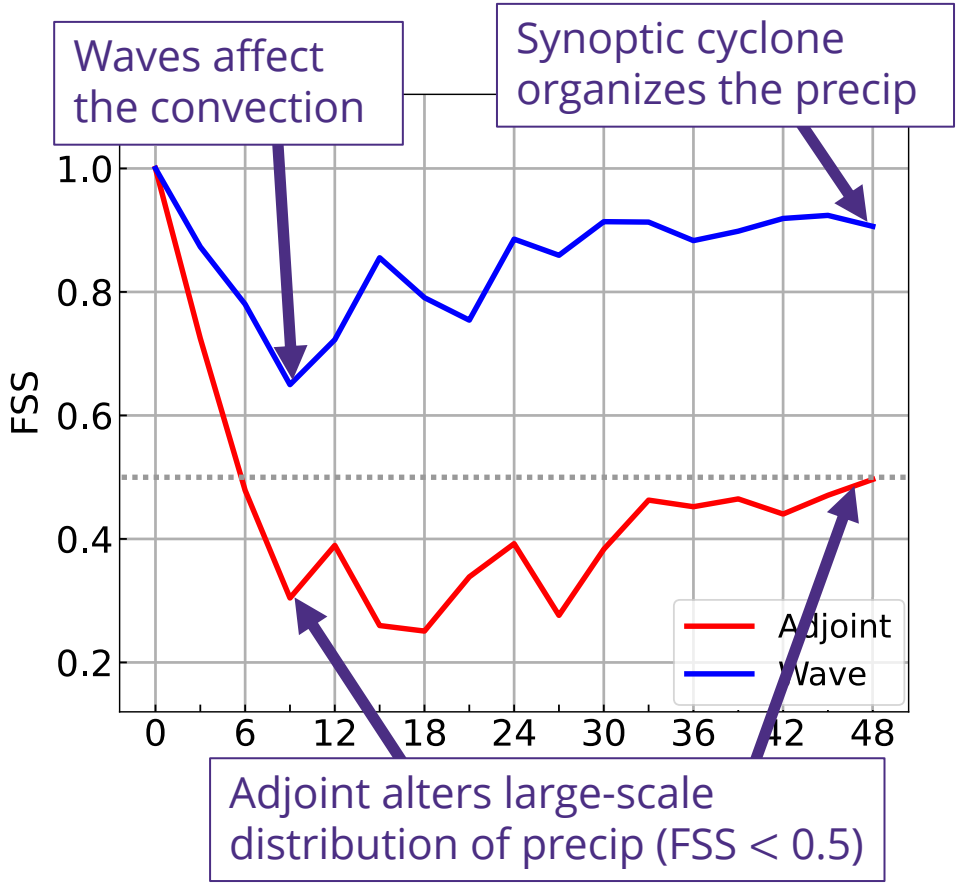


Precipitation changes: fractions skill score (FSS)

Shaded = precip > 1 mm/h
Unshaded = precip ≤ 1 mm/h



FSS = 1 → ctl + pert neighborhoods have same # of points > 1 mm/h → "perfect" forecast



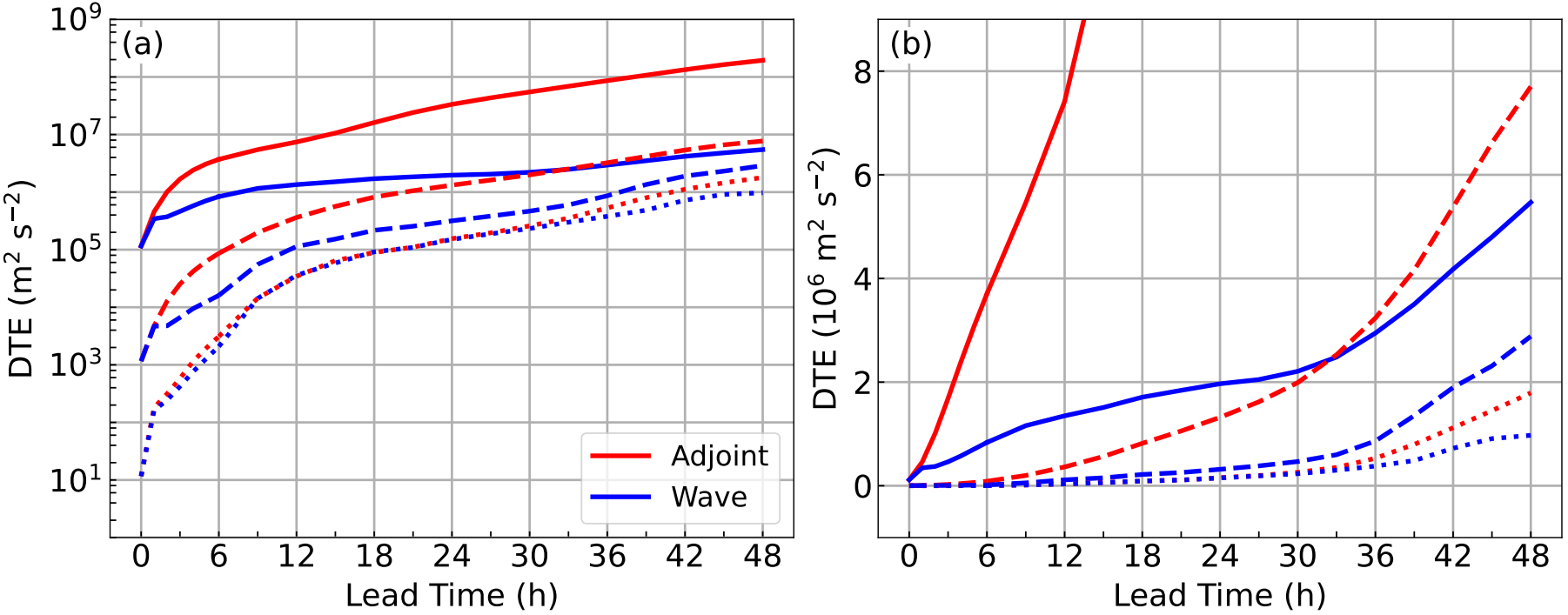
Reducing perturbation magnitude

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

Reducing perturbation magnitude

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

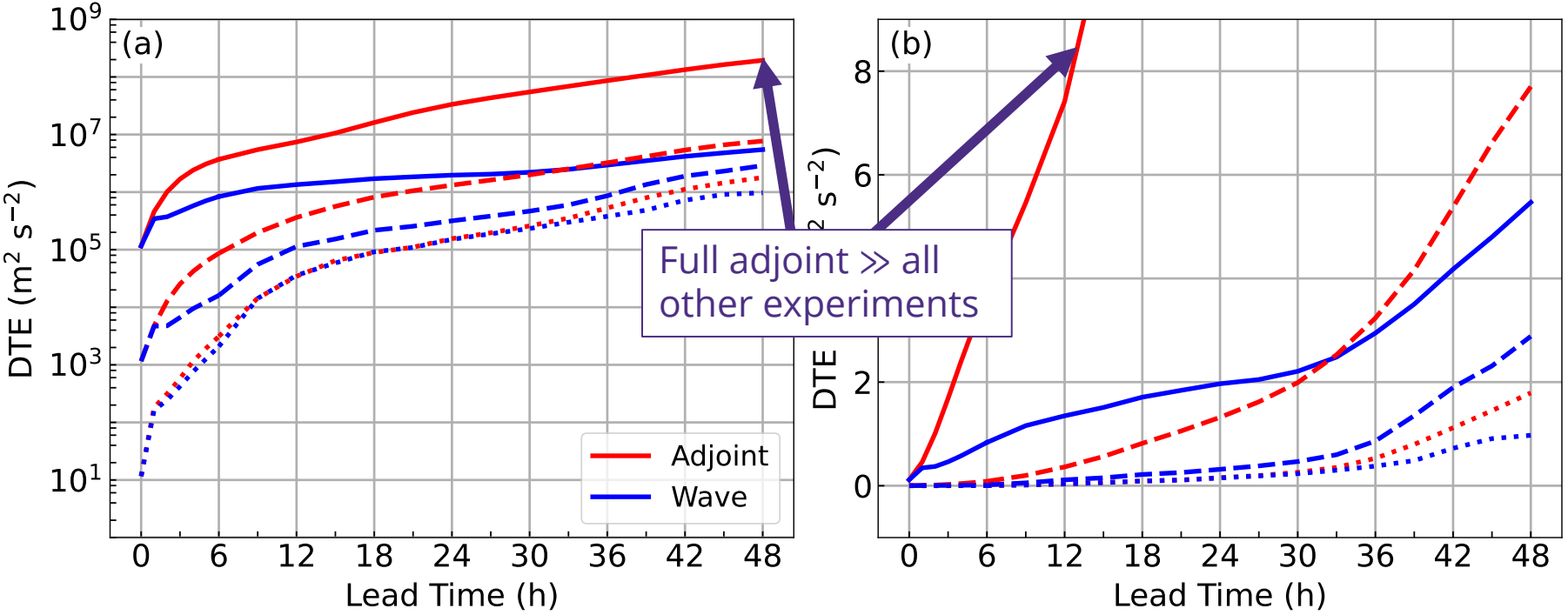
Solid = full; Dashed = 1/10; Dotted = 1/100



Reducing perturbation magnitude

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

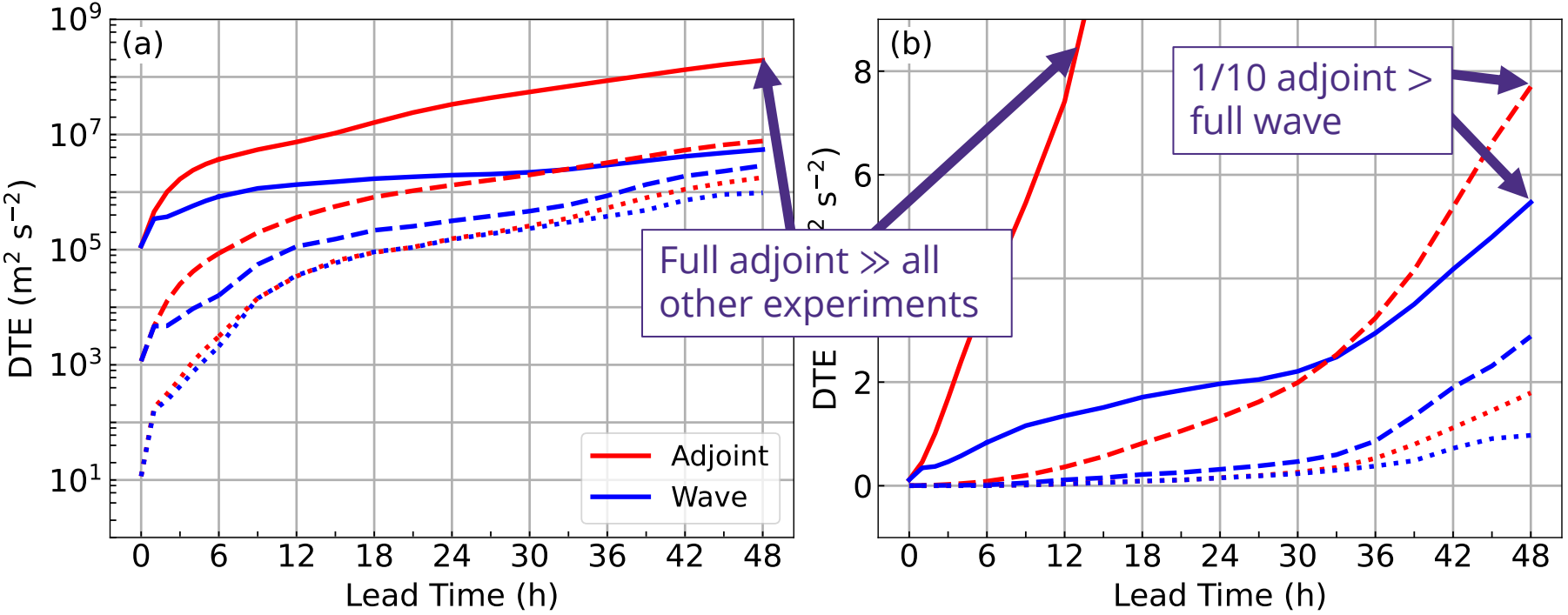
Solid = full; Dashed = 1/10; Dotted = 1/100



Reducing perturbation magnitude

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

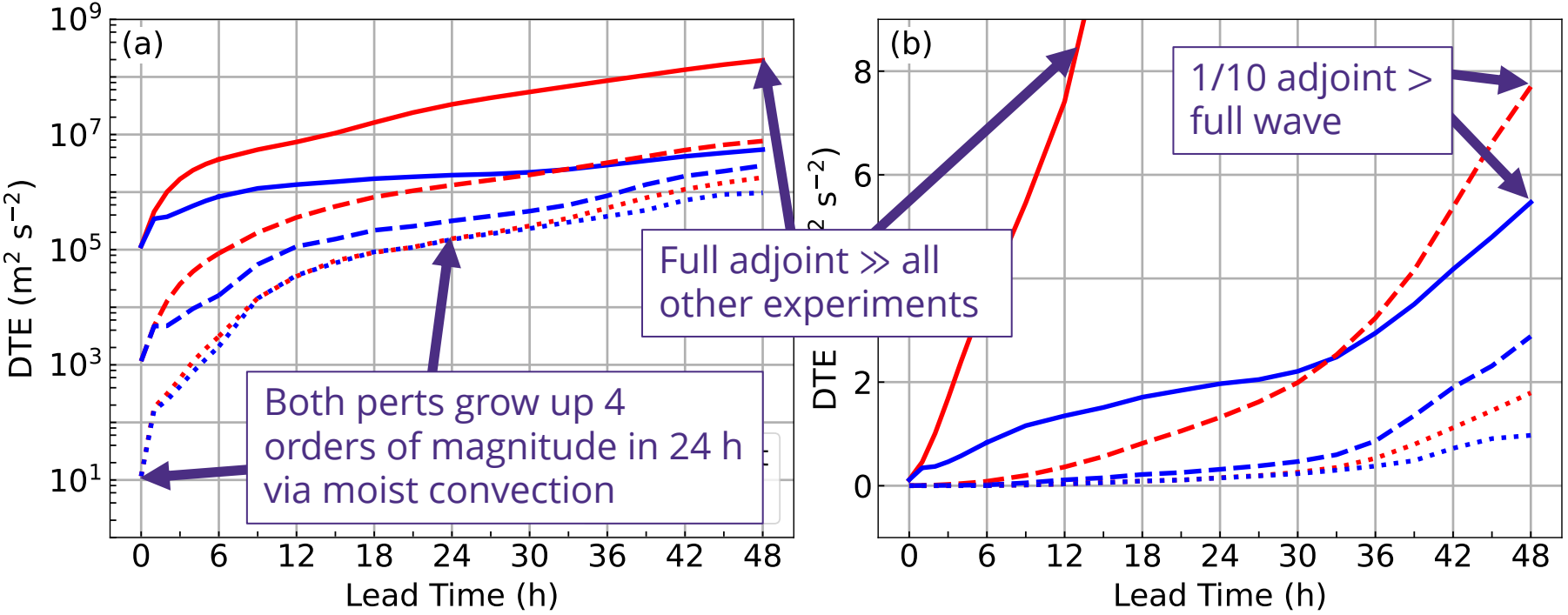
Solid = full; Dashed = 1/10; Dotted = 1/100



Reducing perturbation magnitude

$$\mathrm{DTE} = \frac{1}{2}\left[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2\right],$$

Solid = full; Dashed = 1/10; Dotted = 1/100

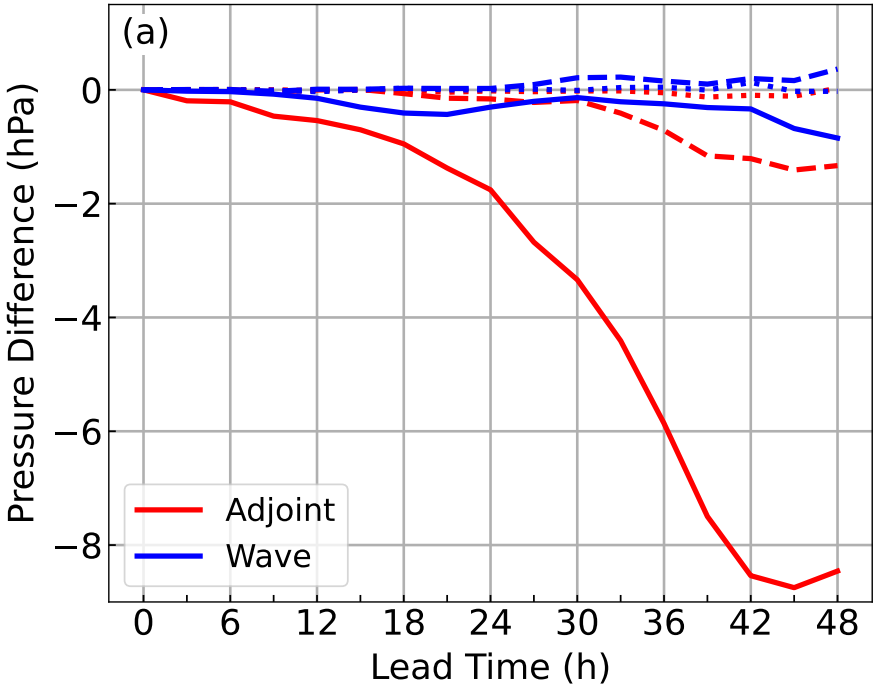


Upscale growth too slow to change cyclone

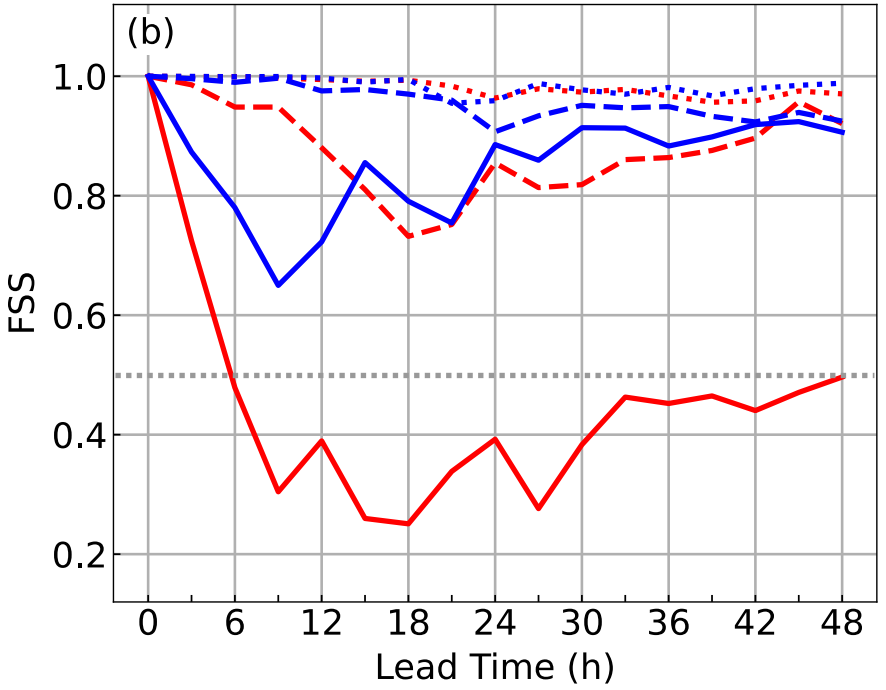
Upscale growth too slow to change cyclone

Solid = full; Dashed = 1/10; Dotted = 1/100

Intensity changes



Precip changes

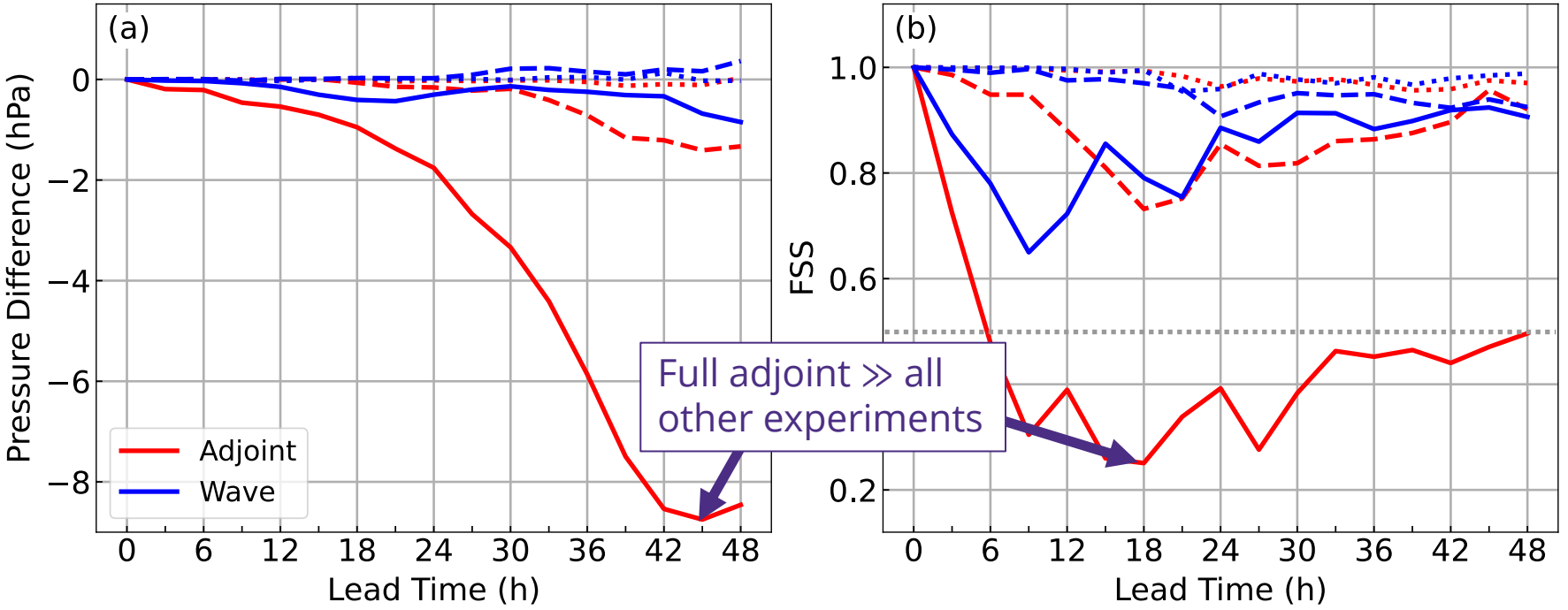


Upscale growth too slow to change cyclone

Solid = full; Dashed = 1/10; Dotted = 1/100

Intensity changes

Precip changes

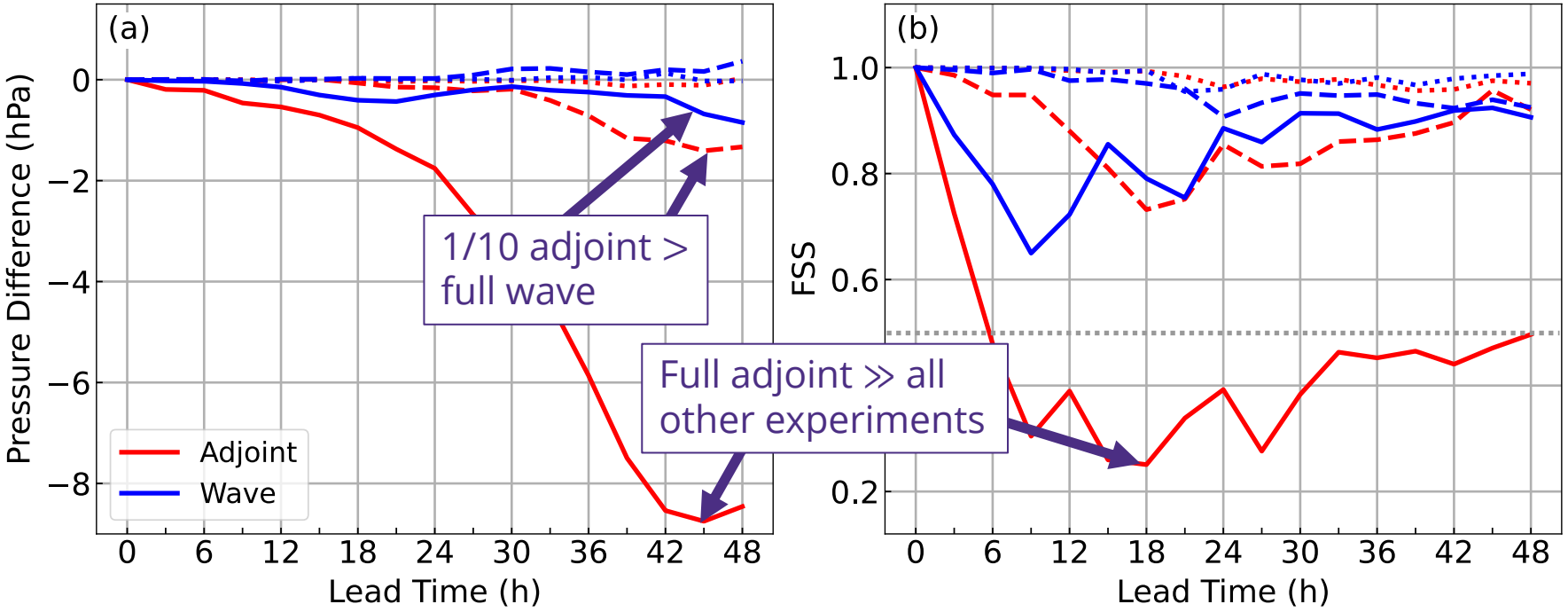


Upscale growth too slow to change cyclone

Solid = full; Dashed = 1/10; Dotted = 1/100

Intensity changes

Precip changes

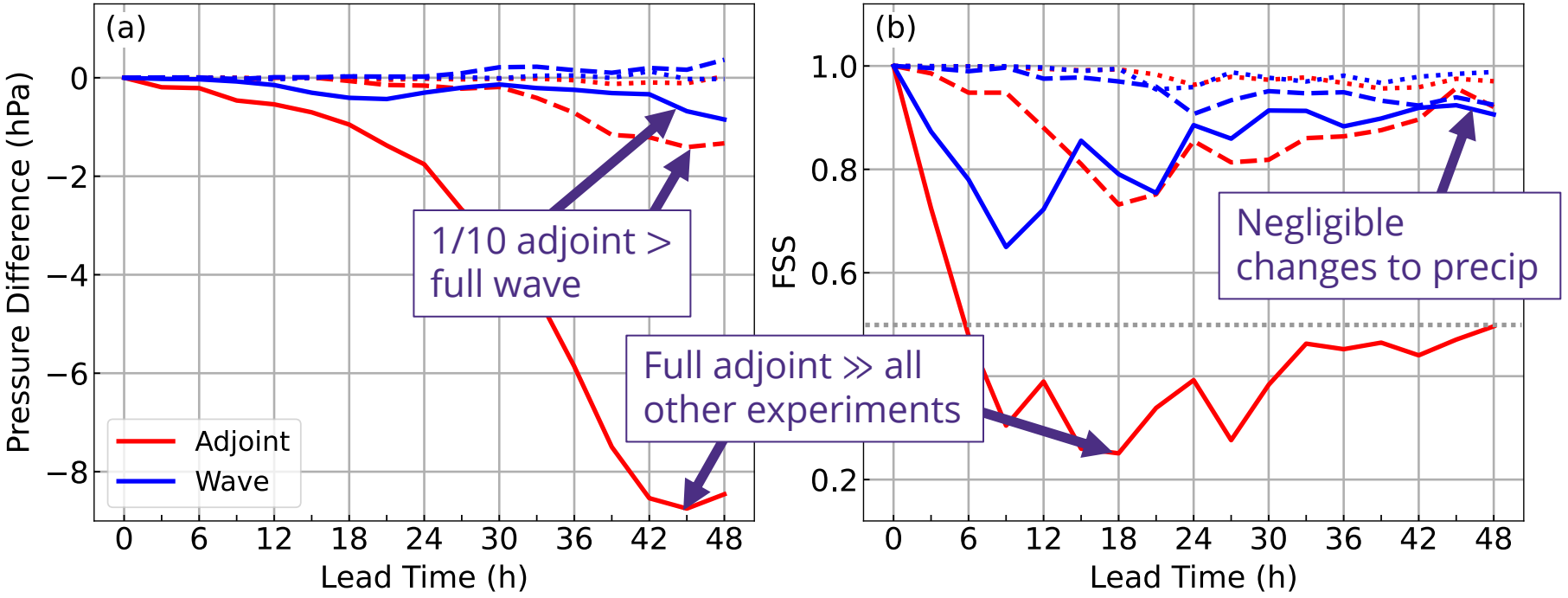


Upscale growth too slow to change cyclone

Solid = full; Dashed = 1/10; Dotted = 1/100

Intensity changes

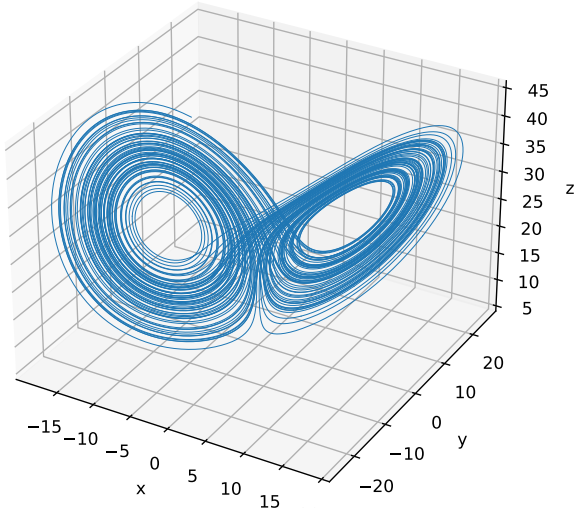
Precip changes



Which Lorenz paper is most relevant to busts?

Which Lorenz paper is most relevant to busts?

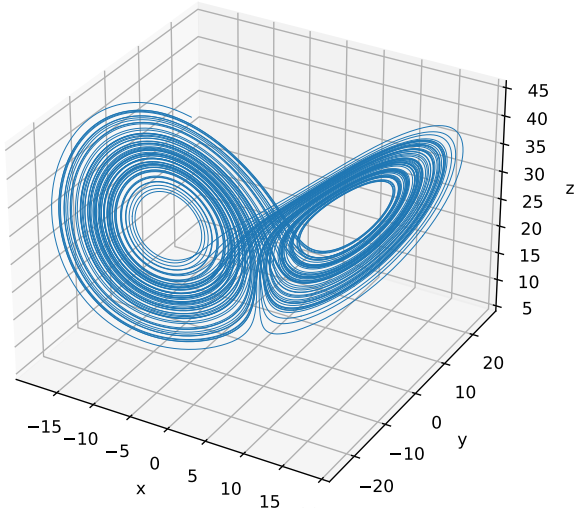
Lorenz (1963): “Chaos”



- Nonlinear system
- Sensitive dependence on initial-conditions

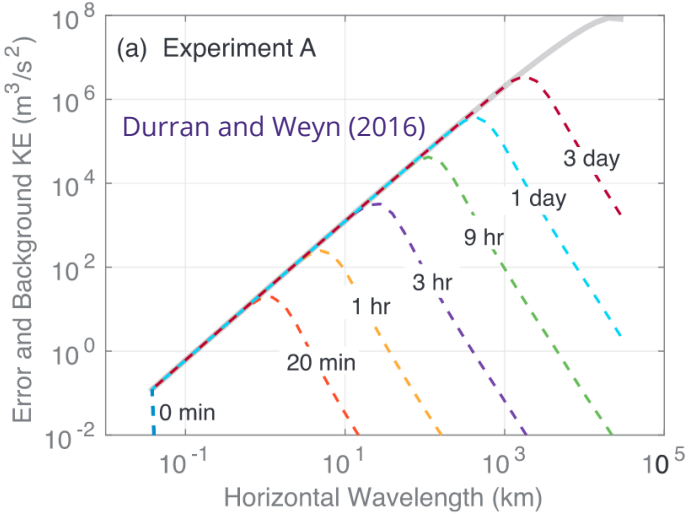
Which Lorenz paper is most relevant to busts?

Lorenz (1963): “Chaos”



- Nonlinear system
- Sensitive dependence on initial-conditions

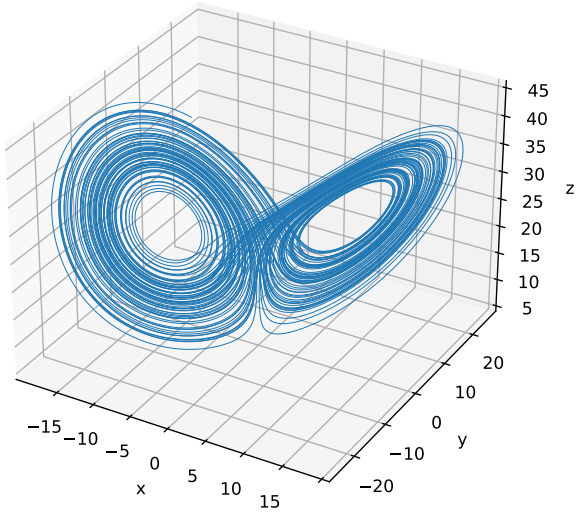
Lorenz (1969): “Butterflies”



- Linear error interactions (with nonlinear saturation)
- Upscale error cascade

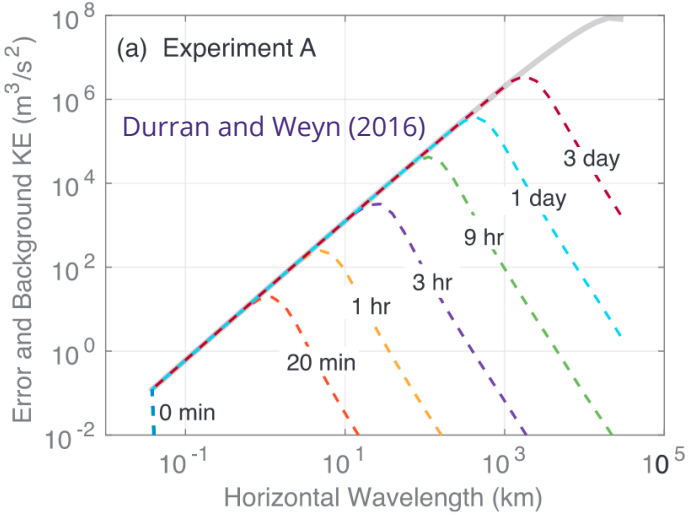
Which Lorenz paper is most relevant to busts?

Lorenz (1963): “Chaos”



> Nonlinear system
> Sensitive dependence on initial-conditions

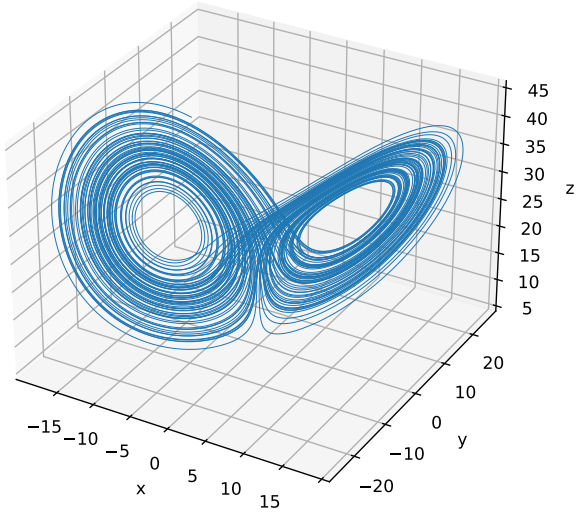
Lorenz (1969): “Butterflies”



> Linear error interactions (with nonlinear saturation)
> ~~Upscale error cascade~~

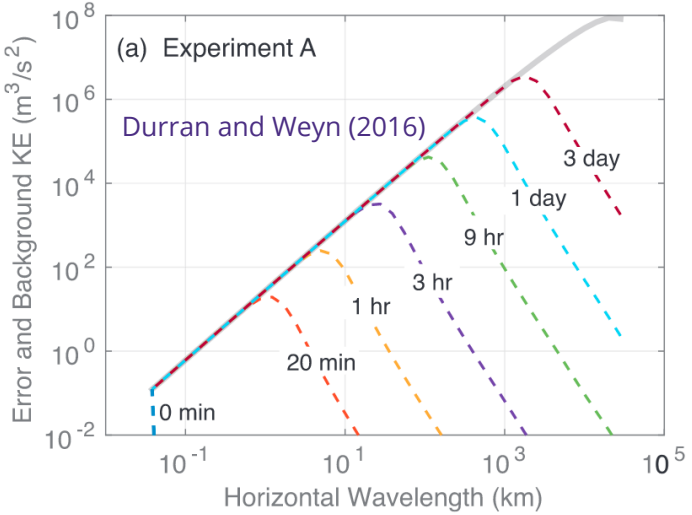
Which Lorenz paper is most relevant to busts?

Lorenz (1963): “Chaos”



> Nonlinear system
> Sensitive dependence on large-scale initial-conditions

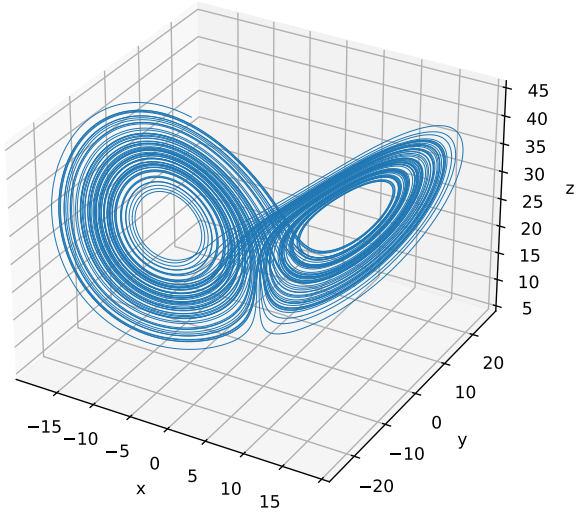
Lorenz (1969): “Butterflies”



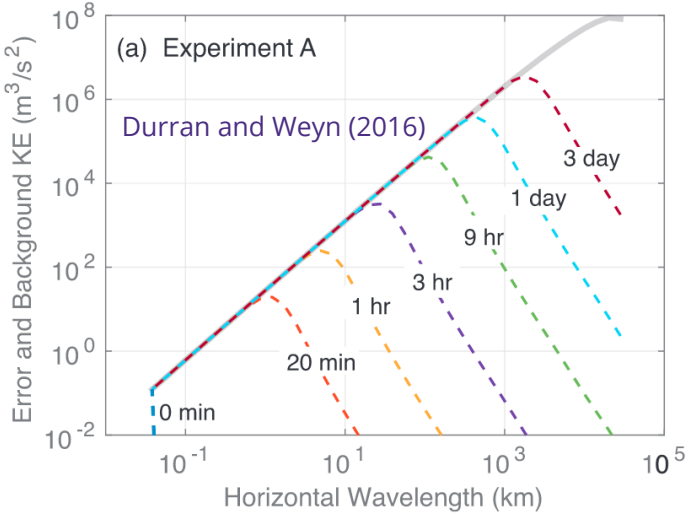
> Linear error interactions (with nonlinear saturation)
> ~~Upscale error cascade~~

Which Lorenz paper is most relevant to busts?

Lorenz (1963): “Chaos”



Lorenz (1969): “Butterflies”



???

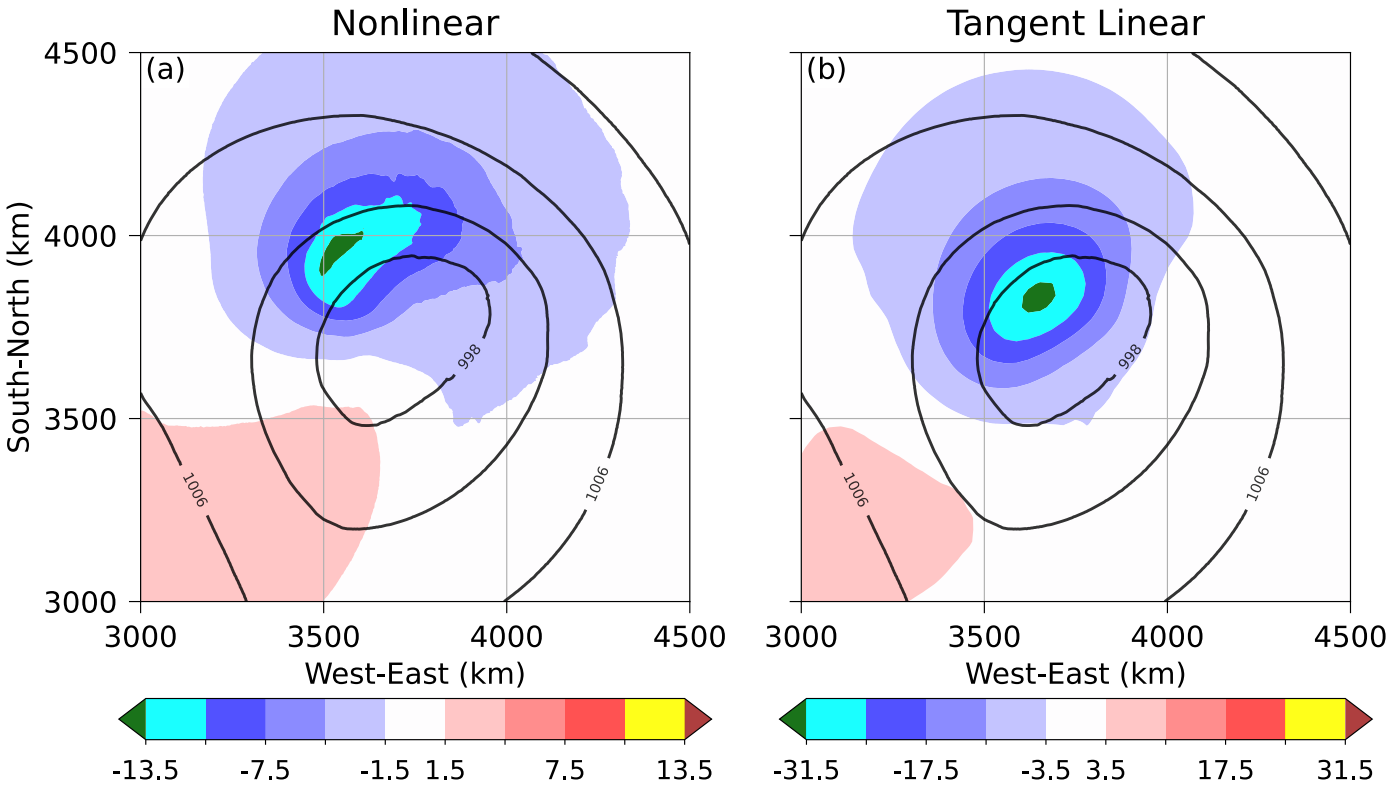
- Nonlinear system
- Sensitive dependence on large-scale initial-conditions

- Linear error interactions (with nonlinear saturation)
- ~~Upscale error cascade~~

Role of nonlinearity

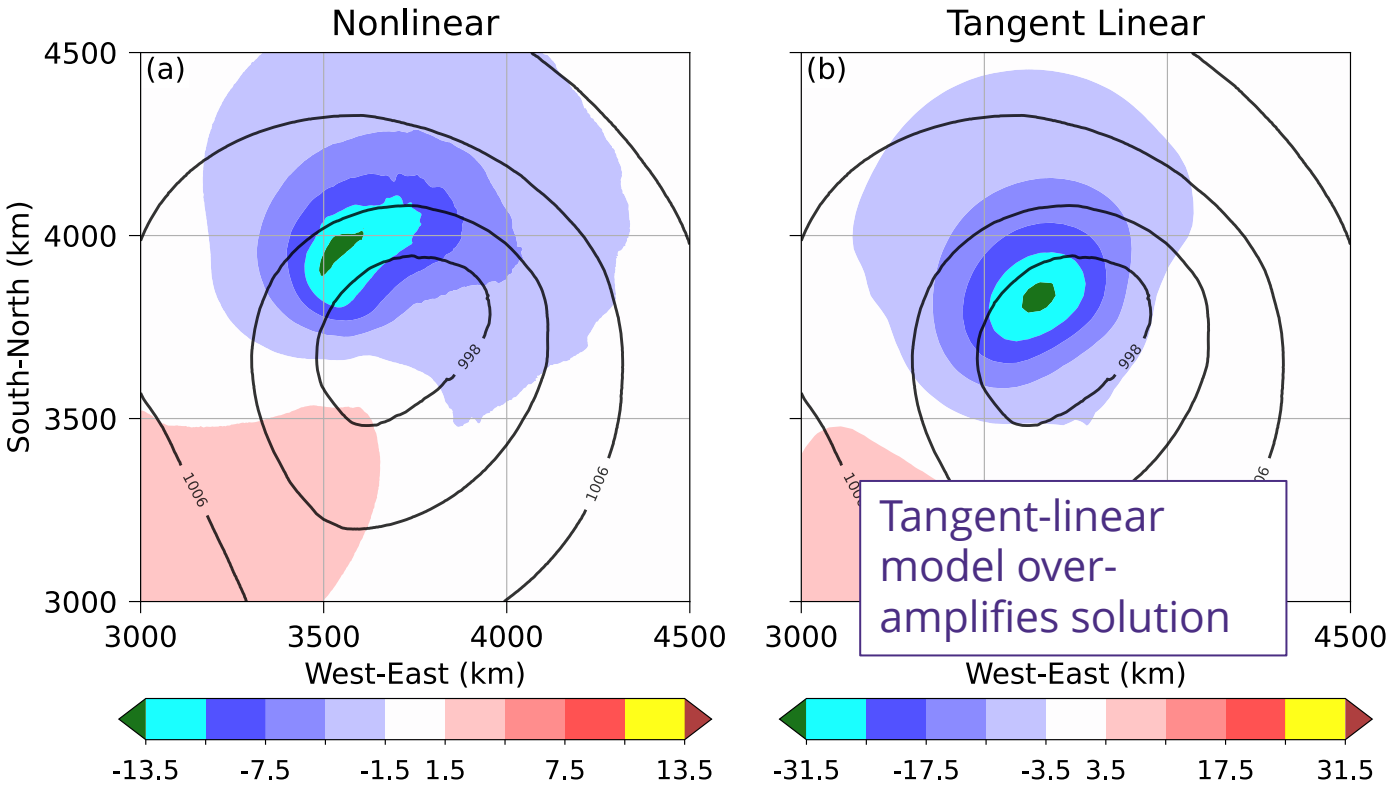
Role of nonlinearity

48-h full-adjoint surface-pressure diff (hPa, *different scales*); Ctl SLP (4 hPa)



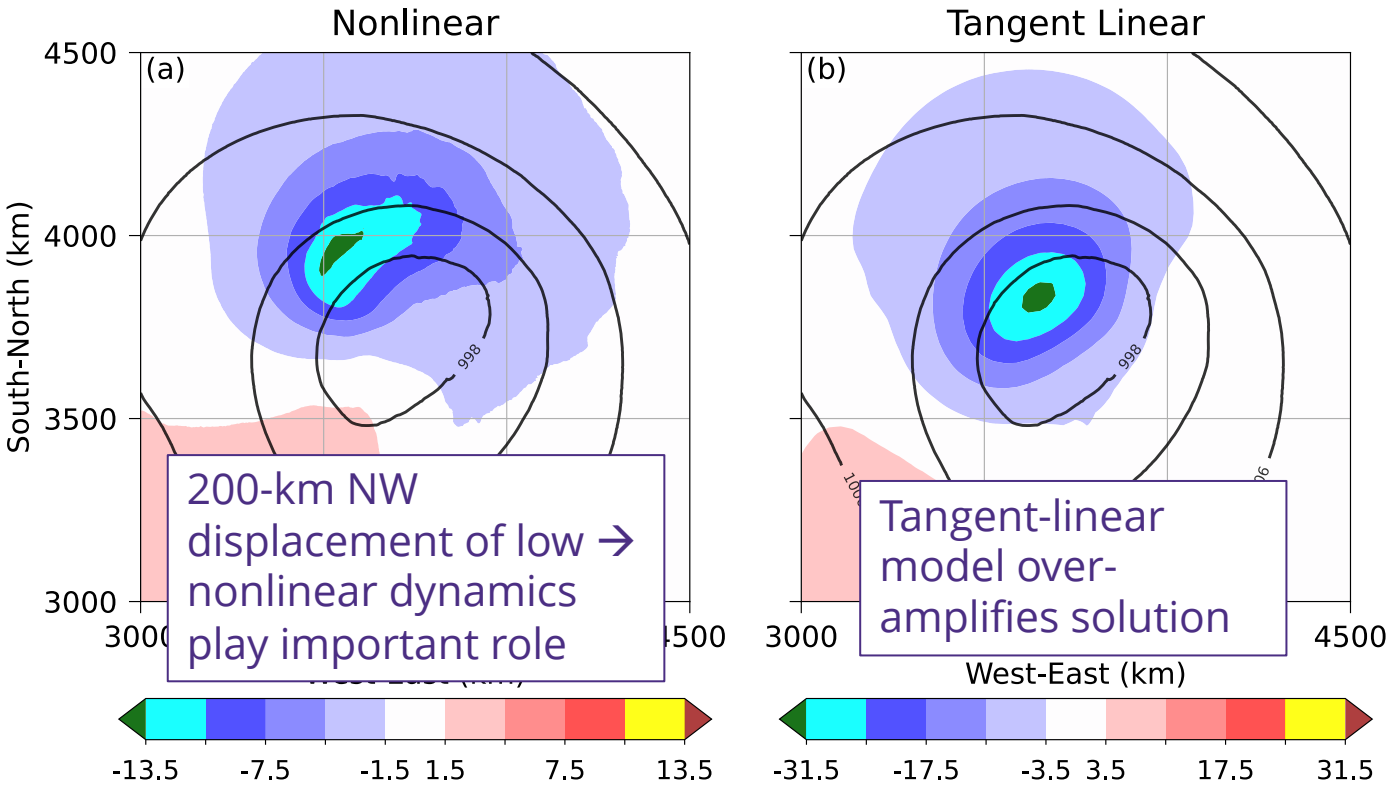
Role of nonlinearity

48-h full-adjoint surface-pressure diff (hPa, *different scales*); Ctl SLP (4 hPa)



Role of nonlinearity

48-h full-adjoint surface-pressure diff (hPa, *different scales*); Ctl SLP (4 hPa)



Conclusions

Conclusions

- For short-range (2–4-day) predictability of midlatitude cyclones:
  - Don’t sweat the small-scale stuff

Conclusions

- For short-range (2–4-day) predictability of midlatitude cyclones:
  - Don’t sweat the small-scale stuff

- Upscale error growth from convection too slow to overcome influence from larger scales
  - Synoptic-scale cyclone organizes distribution of convection

Conclusions

- For short-range (2–4-day) predictability of midlatitude cyclones:
  - Don’t sweat the small-scale stuff

- Upscale error growth from convection too slow to overcome influence from larger scales
  - Synoptic-scale cyclone organizes distribution of convection

- Even weak projection onto large-scale adjoint more impactful than large-magnitude perturbations to convection

Conclusions

- For short-range (2–4-day) predictability of midlatitude cyclones:
  - Don’t sweat the small-scale stuff
- Upscale error growth from convection too slow to overcome influence from larger scales
  - Synoptic-scale cyclone organizes distribution of convection
- Even weak projection onto large-scale adjoint more impactful than large-magnitude perturbations to convection
- Implications: sensitive dependence on synoptic-scale initial conditions (Lorenz 1963) more relevant than upscale error growth (Lorenz 1969)

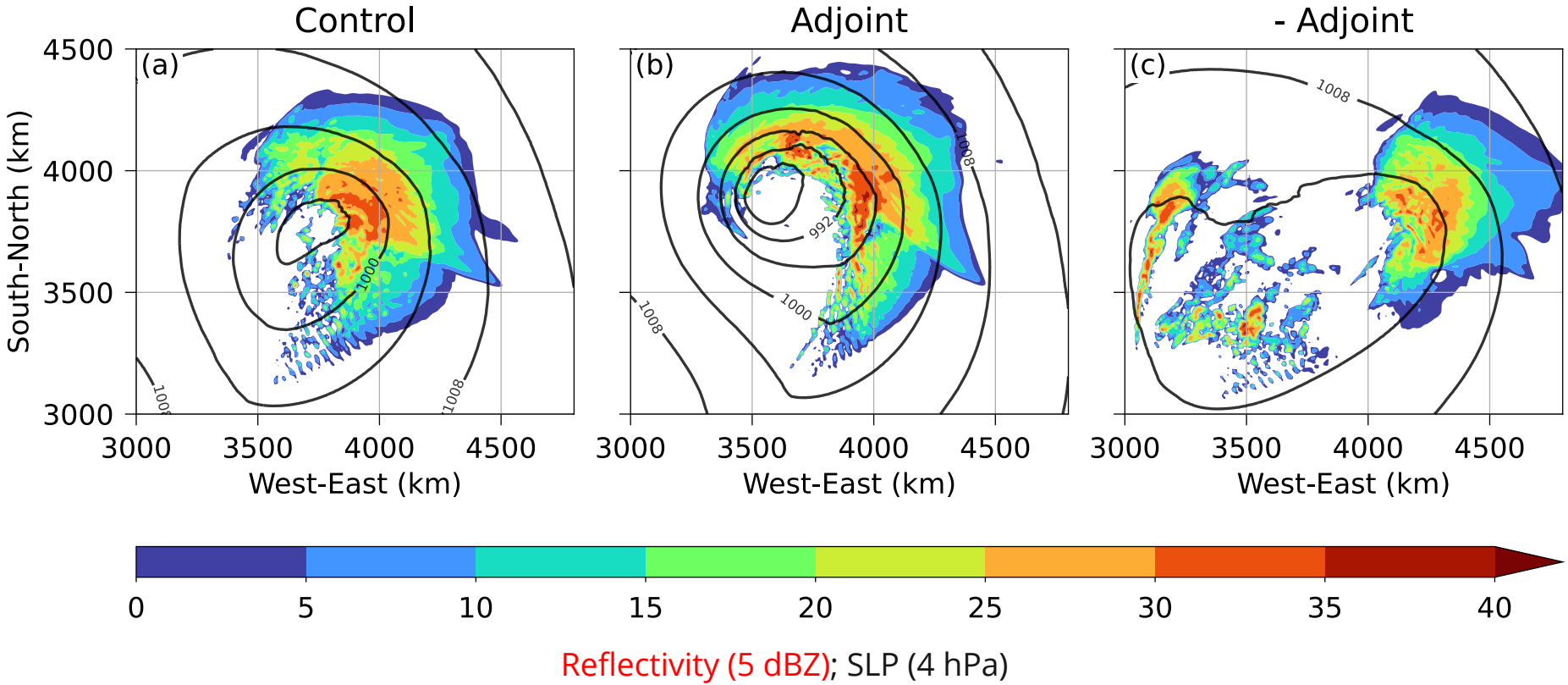
Lloveras, D. J., D. R. Durran, and J. D. Doyle 2023:

The two- to four-day predictability of midlatitude cyclones: Don't sweat the small stuff.

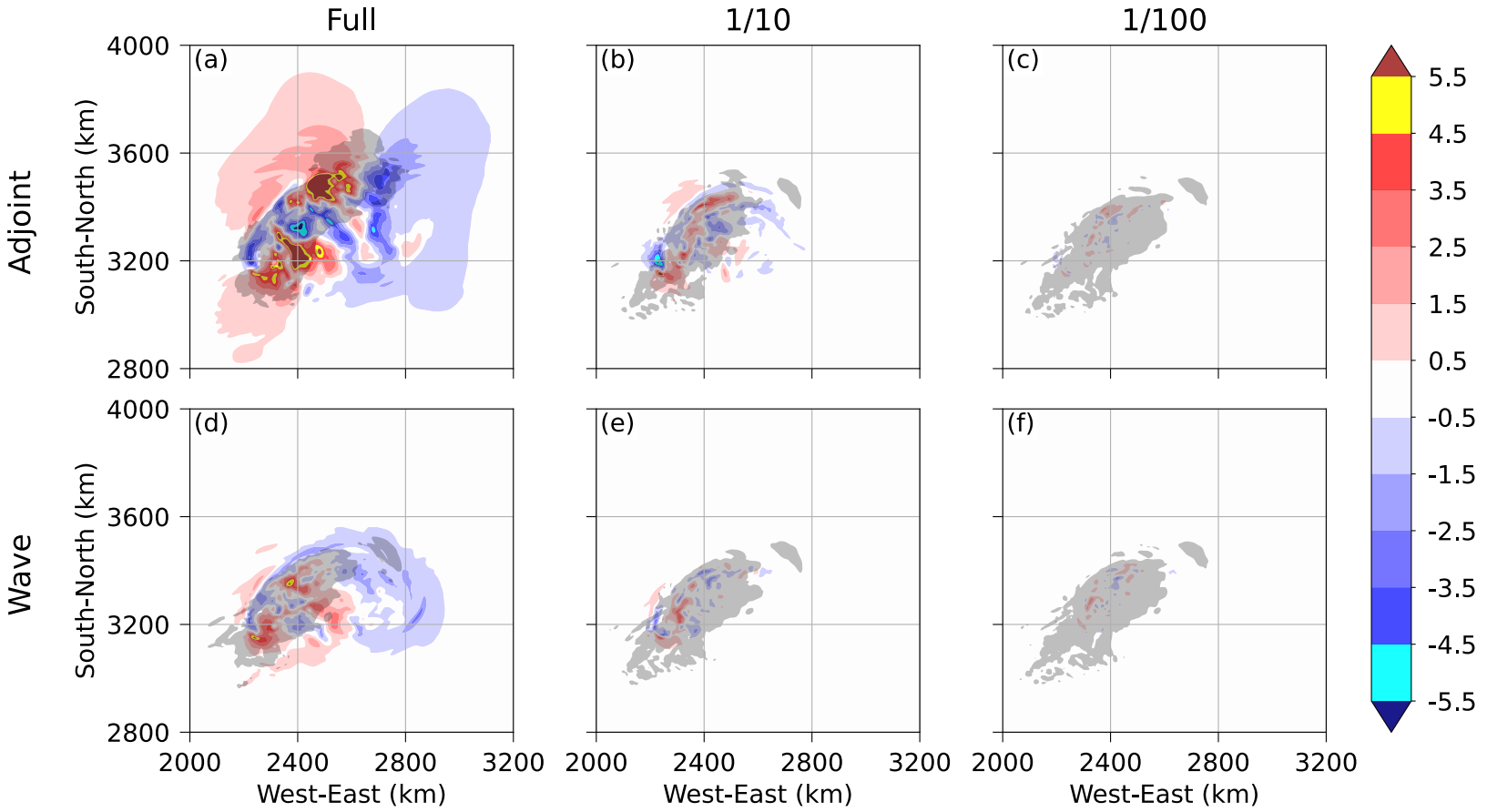
J. Atmos. Sci., in revision.

Thank you!

Changing sign of adjoint perturbations

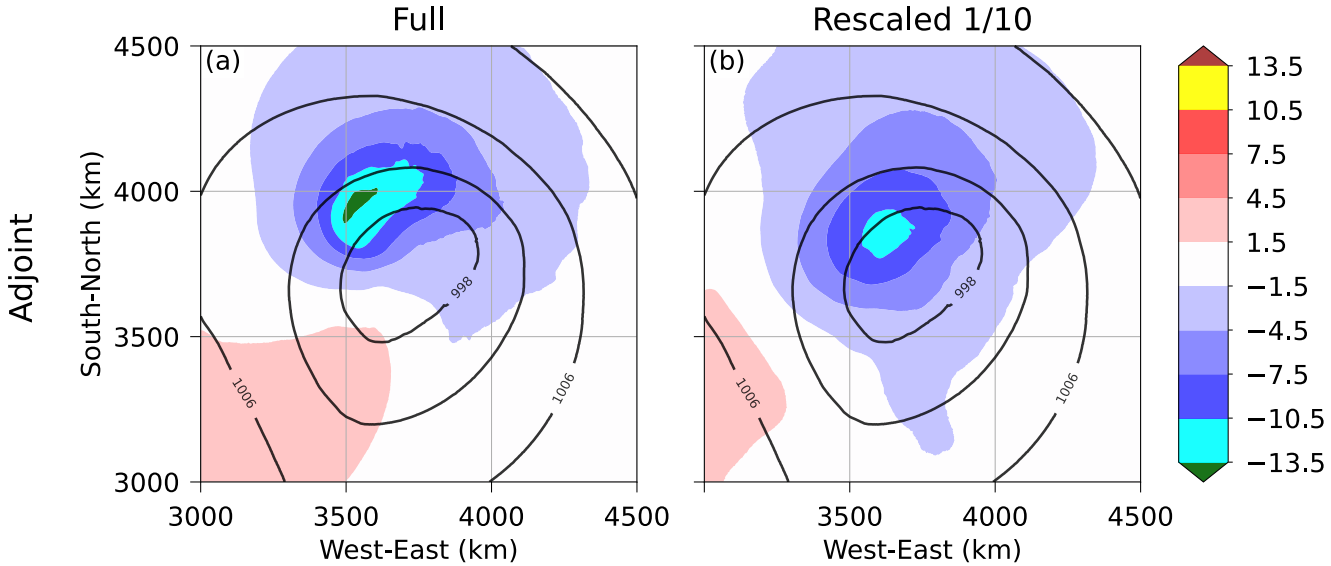


Growth with convection: 12-h δv



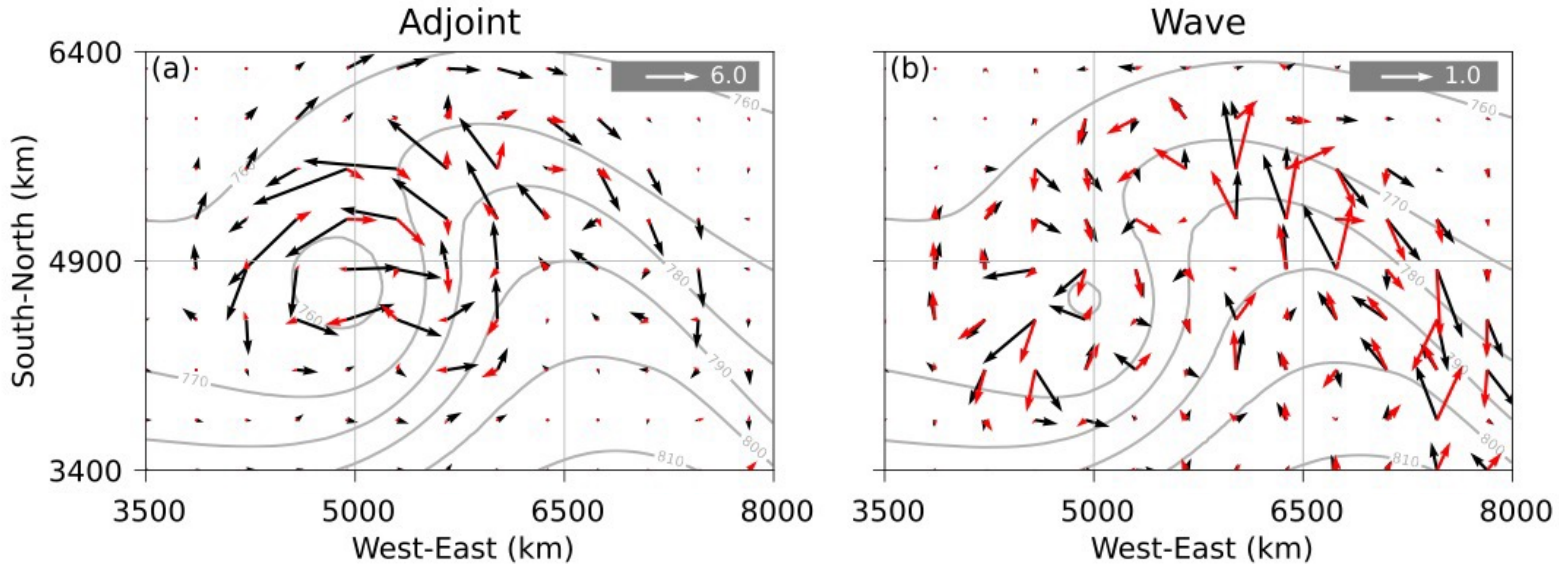
Importance of nonlinearity

- Imitating Lorenz (1969): linear upscale growth until saturation
  - Scale up 1/10 adjoint by factor of 10
  - Reduce saturated wavelengths to background
- Nonlinear effects displace cyclone by ~200 km



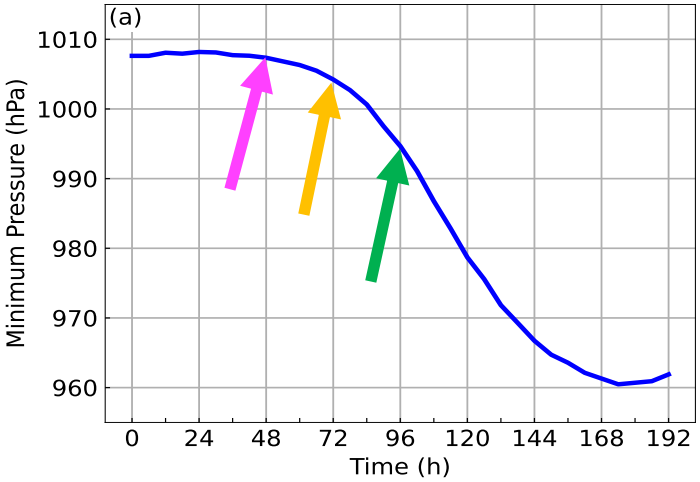
Approach to geostrophic balance

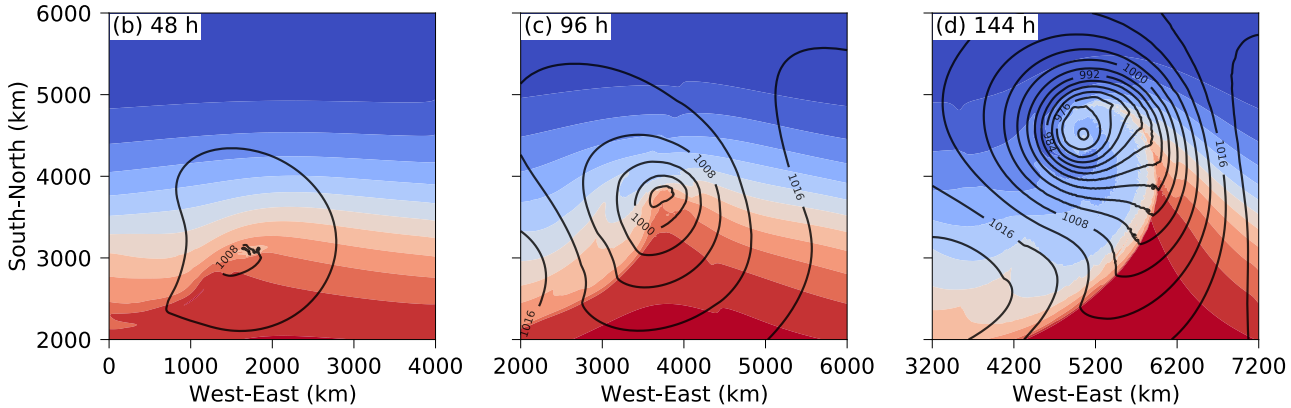
- ~10 h for balanced response to fixed heat source (Bierdel et al. 2017)
- At *96-h* lead times:
  - Filter out wavelengths < 1000 km in 350-hPa winds and heights
  - Compute geostrophic, ageostrophic winds



Does the stage of development matter?

More widespread, vigorous convection + more rapid deepening at later times



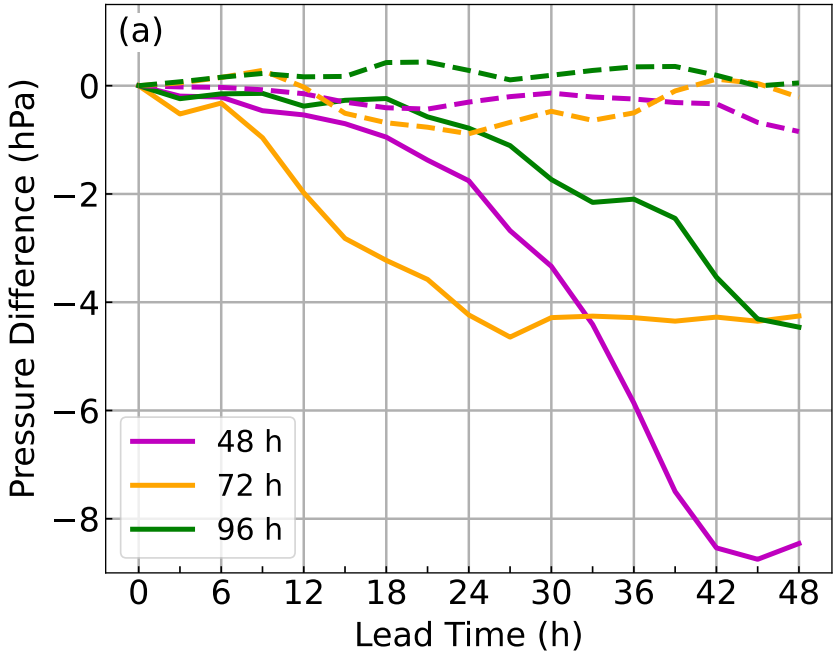


SLP (4 hPa); Surface temperature (2 K)

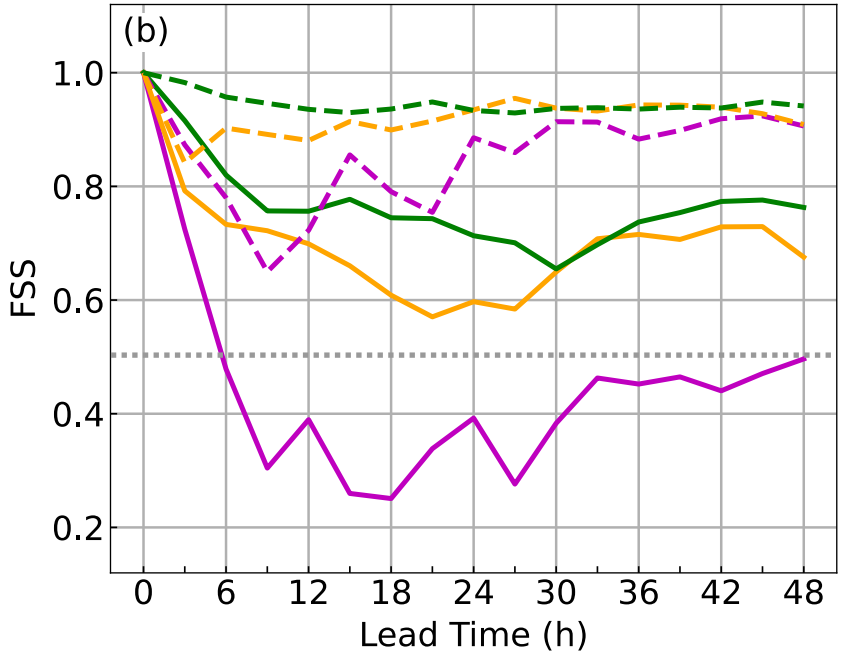
Does the stage of development matter?

Solid = adjoint, dashed = wave

Intensity changes



Precip changes



Perturbations added at 96 h (48-h lead time)