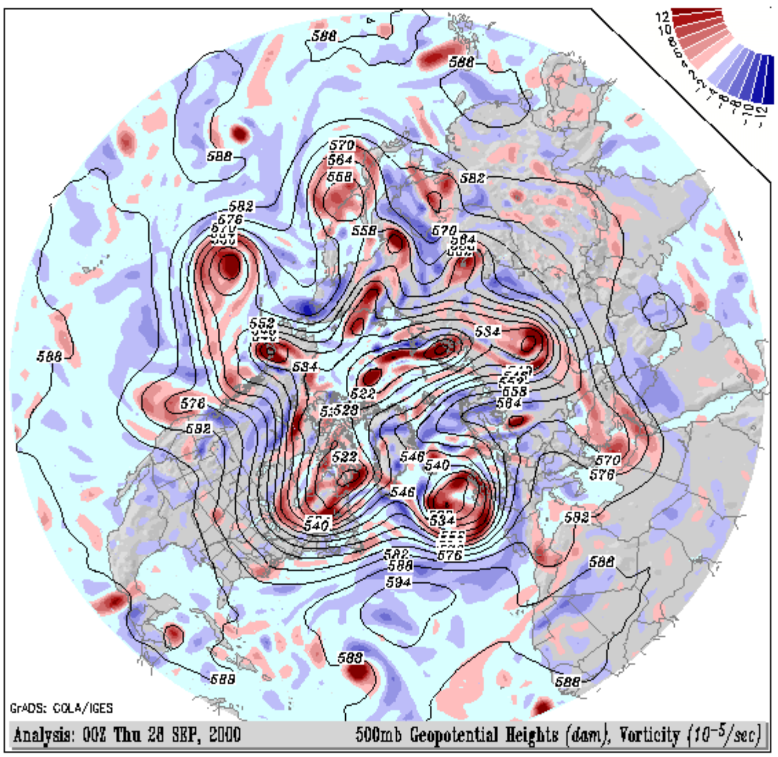
Vortex Asymmetries
in the Midlatitude Atmosphere

rotating, stratified flow

small Rossby number asymptotics (QG+1)

cyclone/anticyclone asymmetries



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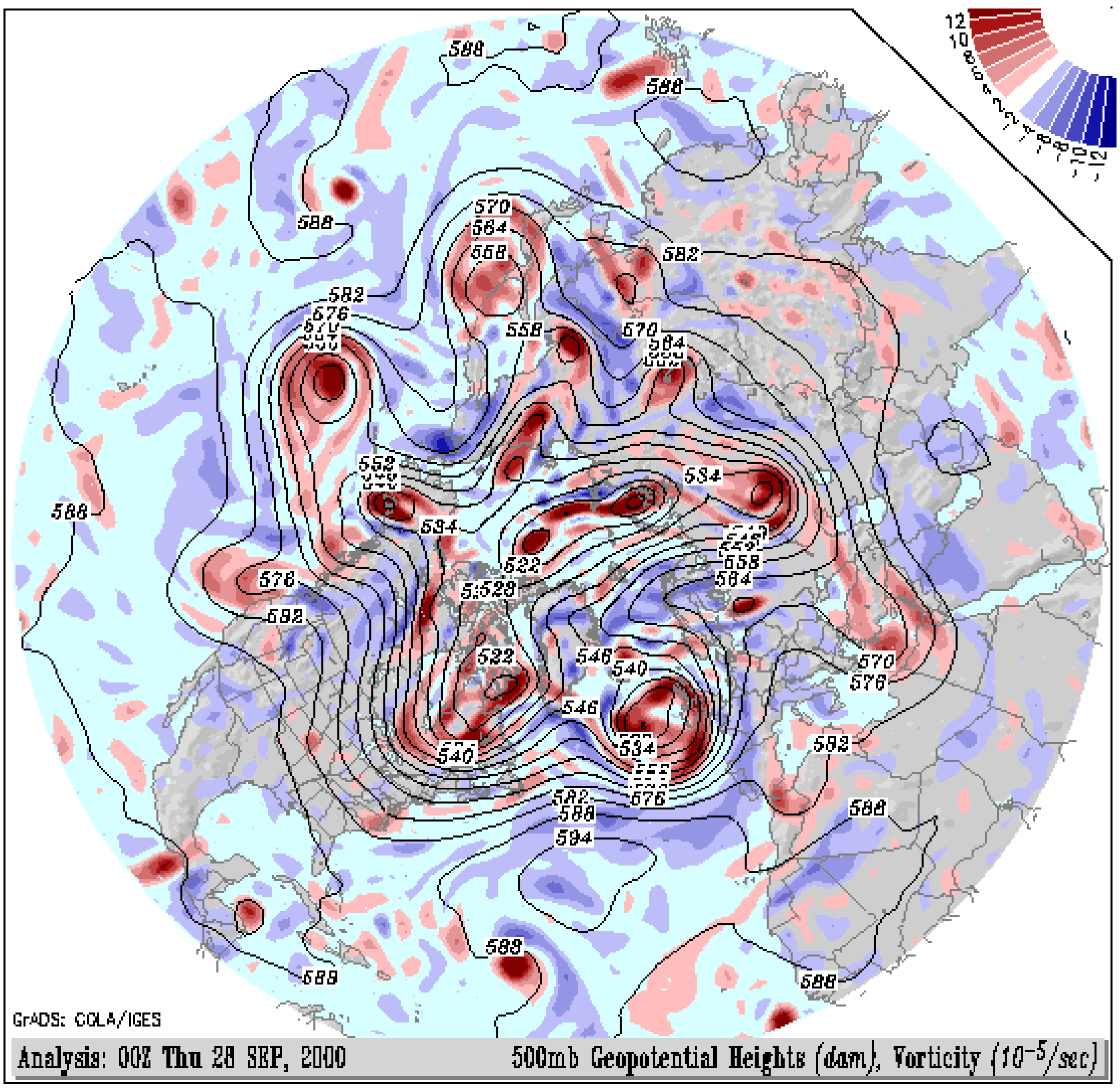
- ▷ Greg Hakim (Univ of Washington)

Vortex Asymmetries I

Jetstream + Pressure Cells → Jet Meanders

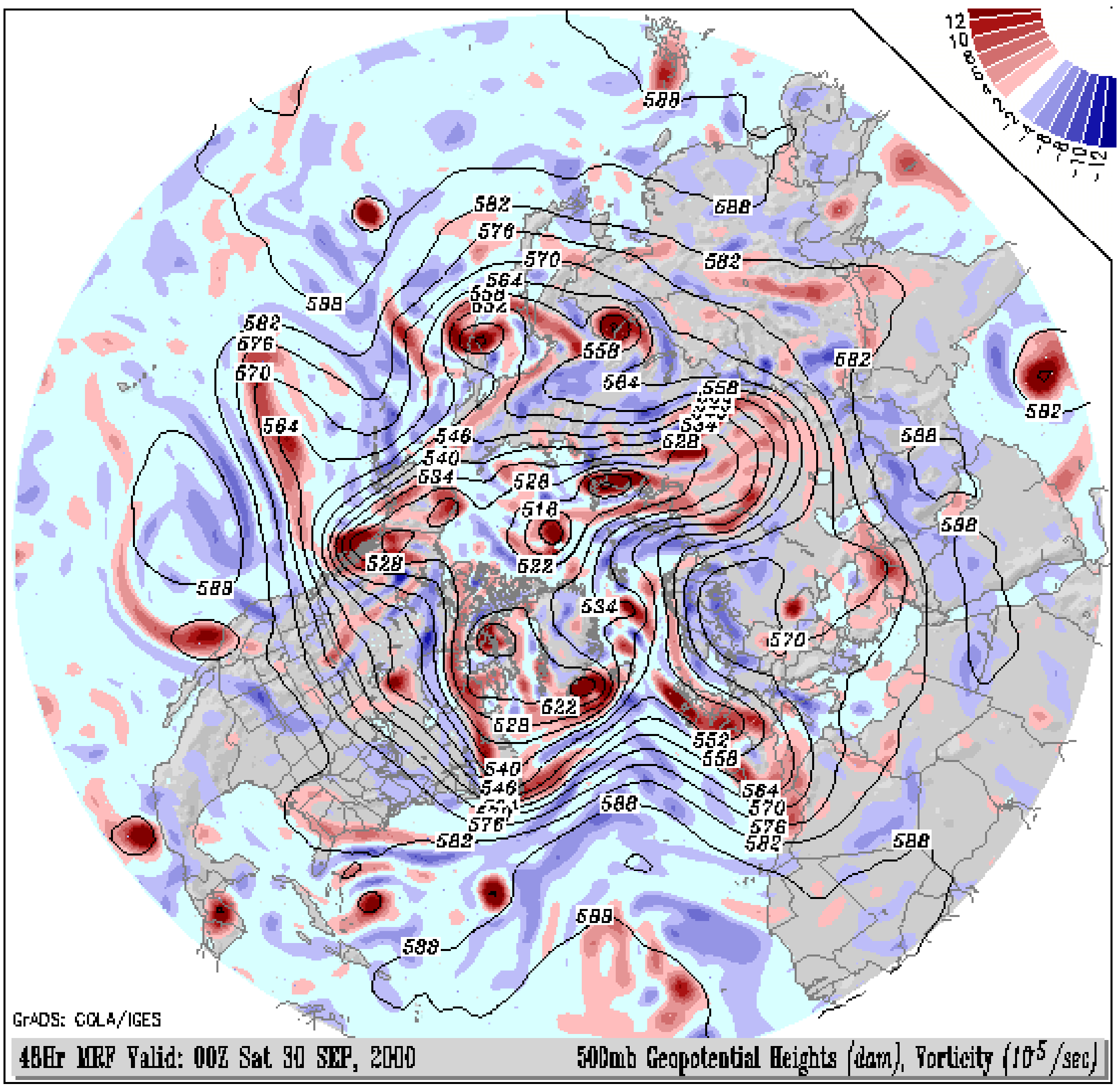
- ▷ 500 hPa vorticity for northern hemisphere (28 sep 00)
- ▷ height contours (black): midlatitude jet
- ▷ cyclones: intense, localized lows → *troughs*
- ▷ anticyclones: broad, weak highs → *ridges*



Vorticity Dynamics

Instability → Variability = Weather

- ▷ 500 hPa vorticity, 48-hr forecast (28 sep 00)
- ▷ vortices advected eastward by jetstream
- ▷ zonal jet unstable to vortices → *baroclinic instability*
- ▷ vortex development & dissipation



Origin of Extratropical Cyclones

A Question of Symmetry-Breaking

- linear baroclinic instability $\to$ *cyclogenesis*
- Q: sources of observed asymmetries?

  $\to$ biased initiation (Sanders 1988)

  $\to$ nonlinear development (Hoskins/West 1979)
- A: both, but . . . key physical mechanisms?

Obstacles & Complications

- 3-dimensional atmospheric flows
- 3 dynamical modes: 1 slow (*balanced*) & 2 fast
- *quasigeostrophy*, leading-order theory is symmetric
- complex interaction of several physical processes

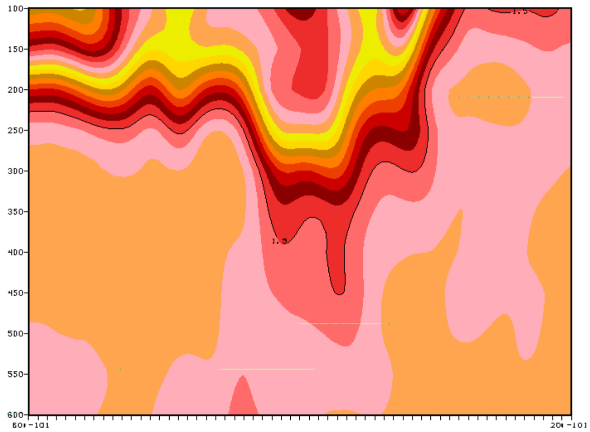
Asymmetric Dynamics

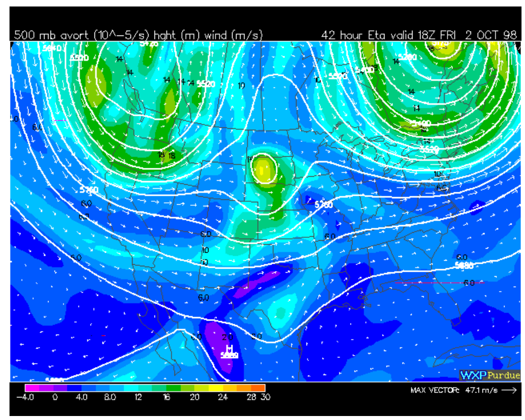
- simple fluid mechanical model
- finite Rossby number corrections (QG^{+1})

Vortex Asymmetries II

Tropopause Disturbances

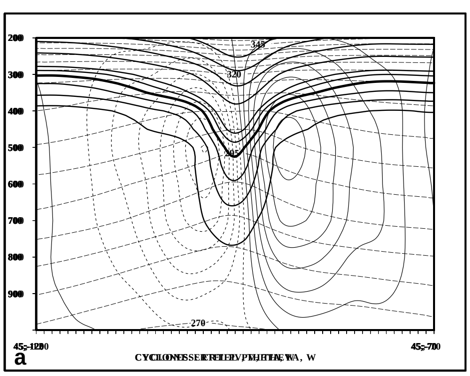
- ▷ midlatitude cyclonic disturbance (02 October 98)
- ▷ N-S vertical profile of potential vorticity (PV)
- ▷ 500 hPa vorticity

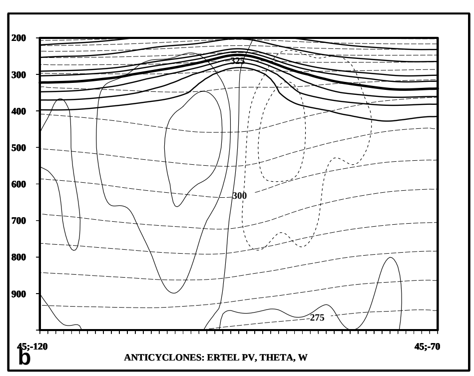




Composite Observations (Hakim 99)

- ▷ zonal section of PV, temperature & vertical motion
- ▷ cyclonic: intense, localized downward deflection
- ▷ anticyclonic: weak, broad upward deflection





Vortex Asymmetries in the Midlatitudes

Cyclone/Anticyclone Asymmetry

- ▷ upper-level troughs as precursors to surface cyclogenesis

  Pettersen (1955), Palmen & Newton (1969)
- ▷ troughs from upper-level cyclonic vorticity, Sanders (1988)

- ▷ localized, intense cyclones & broad, weak anticyclones
- ▷ asymmetries beyond QG balanced dynamics
- ▷ tropopause as organizing level

Geostrophic Turbulence

- ▷ unforced, decaying vortex dynamics

  surface QG (symmetric)

  Pierrehumbert, Held & Swanson (1994)

  Held, Pierrehumbert, Kyle & Swanson (1995)

  2D shallow water *

  Polvani, McWilliams, Spall & Ford (1994)

  3D periodic balance equations *

  Yavneh, Shchepetkin, McWilliams & Graves (1997)

* weak anticyclonic bias at small Rossby number

Atmospheric Model Equations

Thermodynamics & Fluid Mechanics

- incompressible, Boussinesq buoyancy
- inviscid, no thermal diffusion
- rotating (f-plane) & strongly-stratified (stable)
- hydrostatic balance ($\delta \equiv 0$), no moisture

Primitive Equations (PE)

- proto-typical non-dimensional equations

$$
\begin{aligned}
u_x + v_y \quad + \mathcal{R}\, w_z &= 0 \\
\mathcal{R} \left\{ \frac{Du}{Dt} \right\} - v &= -\phi_x \\
\mathcal{R} \left\{ \frac{Dv}{Dt} \right\} + u &= -\phi_y \\
\delta^2 \mathcal{R} \left\{ \frac{Dw}{Dt} \right\} - \theta &= -\phi_z \\
\left\{ \frac{D\theta}{Dt} \right\} + w &= 0
\end{aligned}
$$

- potential temperature: θ is "density^{-1}"

  cold = heavy warm = light

- geopotential: ϕ is "pressure"

Disturbance Equations

$$
\begin{aligned}
u_x + v_y \quad + \mathcal{R}\, w_z &= 0 \\
\mathcal{R} \left\{ \frac{Du}{Dt} \right\} \quad - \quad v &= -\phi_x \\
\mathcal{R} \left\{ \frac{Dv}{Dt} \right\} \quad + \quad u &= -\phi_y \\
- \quad \theta &= -\phi_z \\
\frac{D\theta^F}{Dt} = \left\{ \frac{D\theta}{Dt} \right\} \quad + \quad w &= 0
\end{aligned}
$$

Stratification

- small Rossby number: $\mathcal{R} = \dfrac{\mathcal{U}}{fL} \ll 1$
- strongly-stratified base state: $\theta^F = \dfrac{1}{\mathcal{R}}\, z + \theta$
- nonlinearity in advection (weak in vertical)

$$\frac{D}{Dt} \equiv \partial_t + u\,\partial_x + v\,\partial_y + \mathcal{R}\, w\,\partial_z$$

- advection of potential vorticity: $\dfrac{Dq}{Dt} = 0$

$$q \equiv \{v_x - u_y + \theta_z\} + \mathcal{R}\, \{(v_x - u_y)\,\theta_z - v_z\,\theta_x + u_z\,\theta_y\}$$

Quasigeostrophic Theory (QG)

Zero Rossby number ($\mathcal{R} = 0$)

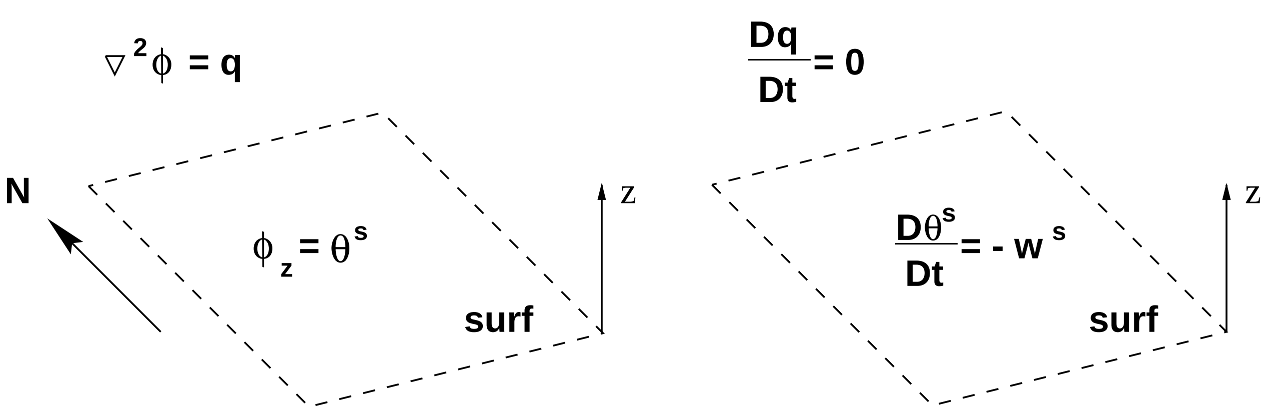
- Charney (1947) & Eady (1949)
- single-potential representation $\phi(x, y, z, t)$

$$\begin{aligned} v &= \phi_x \\ -u &= \phi_y \\ \theta &= \phi_z \\ -w &= \frac{D\theta}{Dt} \end{aligned}$$

- ϕ is a 2-D streamfunction, continuity for free
- "missing" ϕ-dynamics $\longrightarrow$ geostrophic degeneracy

Potential Vorticity

- 2 steps: inversion $\longleftrightarrow$ dynamics

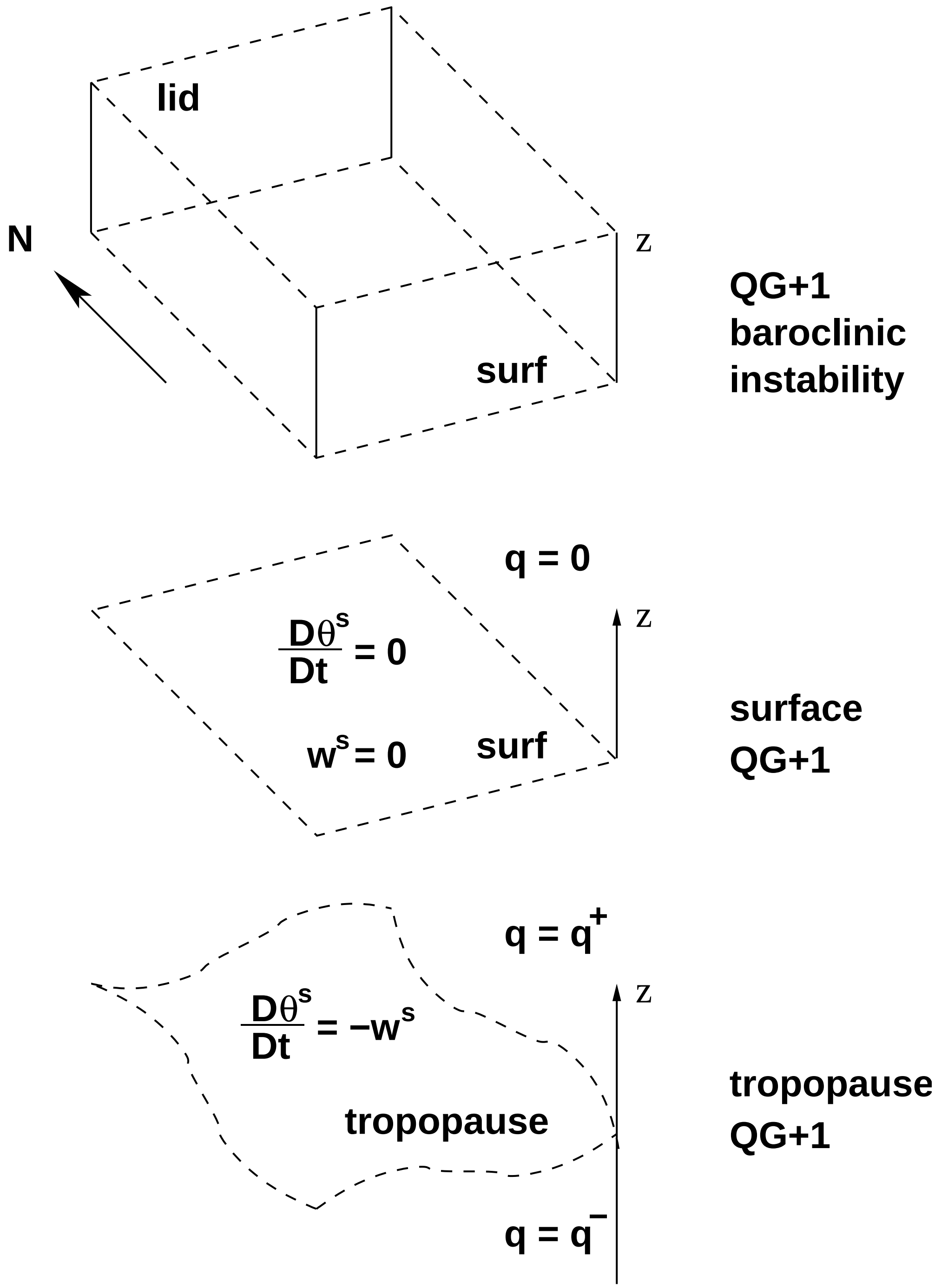


- $q \equiv 0 \rightarrow$ surface QG: computationally 2-D

sQG Atmospheric Configurations

Boundary Conditions

- rigid surface/lid, rigid surface & material interface
- sQG: uniform PV interior, surface dynamics



QG+ Reformulation

Exact Reformulation of PE

- three-potential representation: Φ, F, G

$$\begin{aligned} v &= \Phi_x - G_z \\ -u &= \Phi_y + F_z \\ \theta &= \Phi_z + G_x - F_y \\ \mathcal{R}\, w &= F_x + G_y \end{aligned}$$

- potential inversions

$$\begin{aligned} \nabla^2 \Phi &= q - \mathcal{R} \left\{ \nabla \cdot \left[\theta \left(\nabla \times \vec{\mathbf{u}}_H \right) \right] \right\} \\ \nabla^2 F &= \mathcal{R} \left\{ - \left(\frac{D\theta}{Dt} \right)_x + \left(\frac{Dv}{Dt} \right)_z \right\} \\ \nabla^2 G &= \mathcal{R} \left\{ - \left(\frac{D\theta}{Dt} \right)_y - \left(\frac{Du}{Dt} \right)_z \right\} \end{aligned}$$

- surface boundary conditions

$$(F_x + G_y)^s = \mathcal{R}\, w^s \quad , \quad (\Phi_z + G_x - F_y)^s = \theta^s$$

- advection dynamics

$$\frac{Dq}{Dt} = 0 \quad , \quad \frac{D\theta^s}{Dt} = -\, w^s$$

QG+ Asymptotic Dynamics

Balanced Expansion

- ▷ $\mathcal{R} = 0$ recovers QG theory, no gravity waves
- ▷ QG+ balanced expansion:

$$\begin{aligned} \Phi &= \Phi^0 + \mathcal{R}\,\Phi^1 + \ldots \\ F &= \mathcal{R}\,F^1 + \ldots \\ G &= \mathcal{R}\,G^1 + \ldots \end{aligned}$$

- ▷ QG+1 truncation: next-order corrections

Gravity Wave Expansion

- ▷ wave expansion: $F, G = O(1)$; $\Phi, q = O(\mathcal{R})$

$$\begin{aligned} \Phi &= \mathcal{R}\,\Phi^1 + \ldots \\ F &= F^0 + \mathcal{R}\,F^1 + \ldots \\ G &= G^0 + \mathcal{R}\,G^1 + \ldots \end{aligned}$$

- ▷ fast-scale linear wave equation $\longrightarrow$ gravity waves

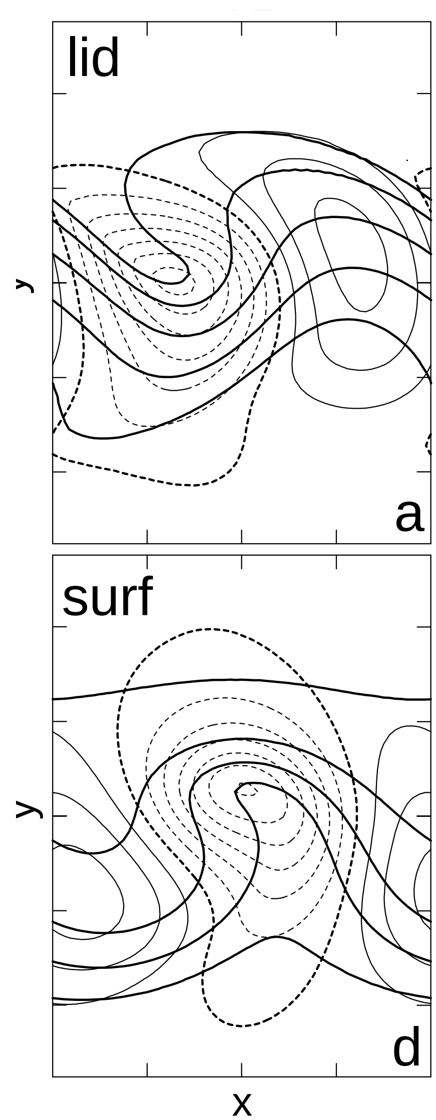
$$\begin{aligned} \nabla^2 F &+ \mathcal{R}\,\{(G_x - F_y)_x + G_{zz}\}_t &= O(\mathcal{R}) \\ \nabla^2 G &+ \mathcal{R}\,\{(G_x - F_y)_y - F_{zz}\}_t &= O(\mathcal{R}) \end{aligned}$$

- ▷ linear gravity wave dispersion relation

Baroclinic Instability

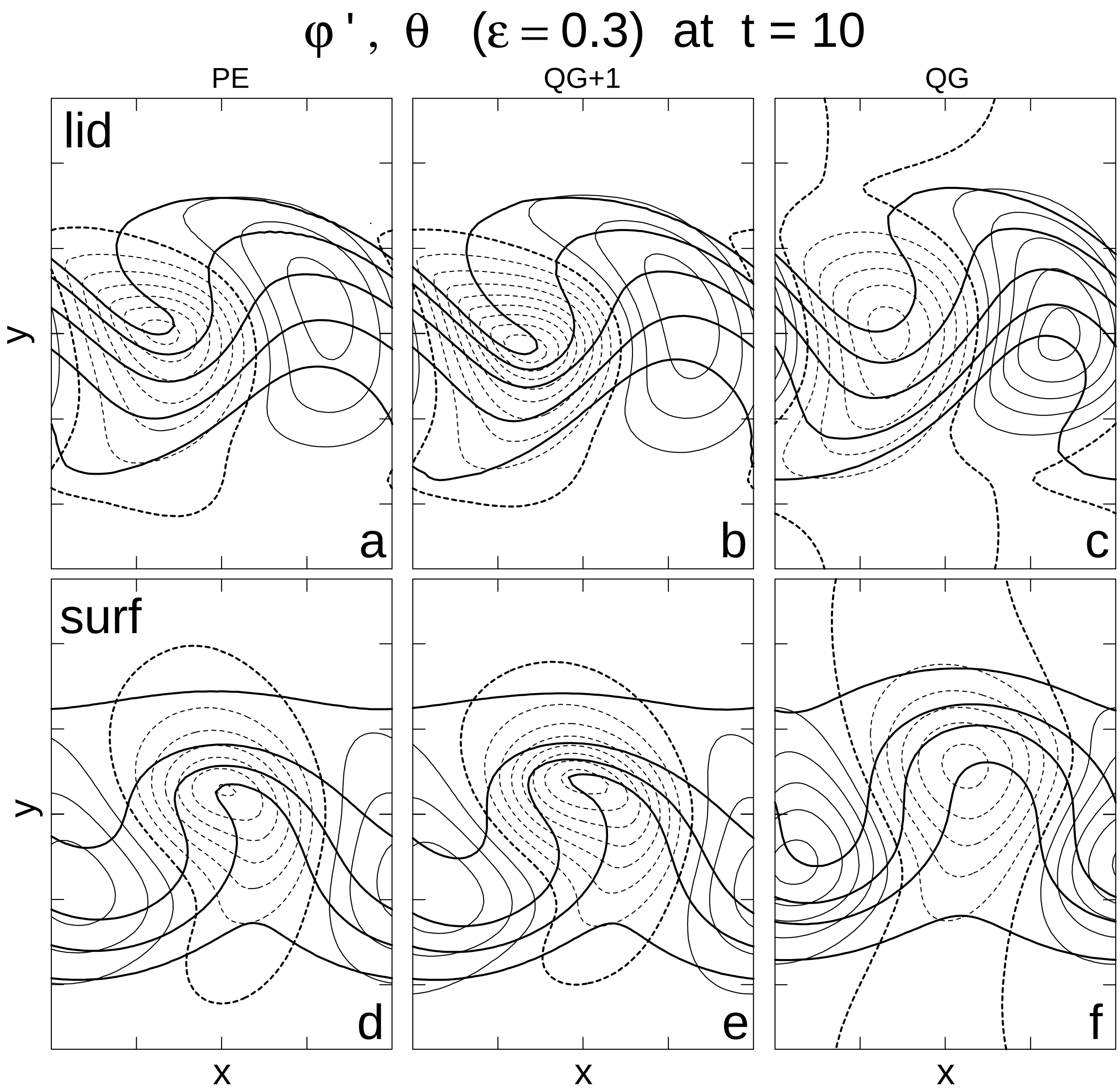
Norwegian Cyclone Model

- ▷ Bjerknes & Solberg (1926)
- ▷ Hoskins & West (1979), unstable jet computation



Baroclinic Wave Development

- ▷ PE: primitive equations, PDE fluid model
- ▷ QG+1, QG: asymptotic reductions
- ▷ isobars (ϕ) & isoentropes (θ)

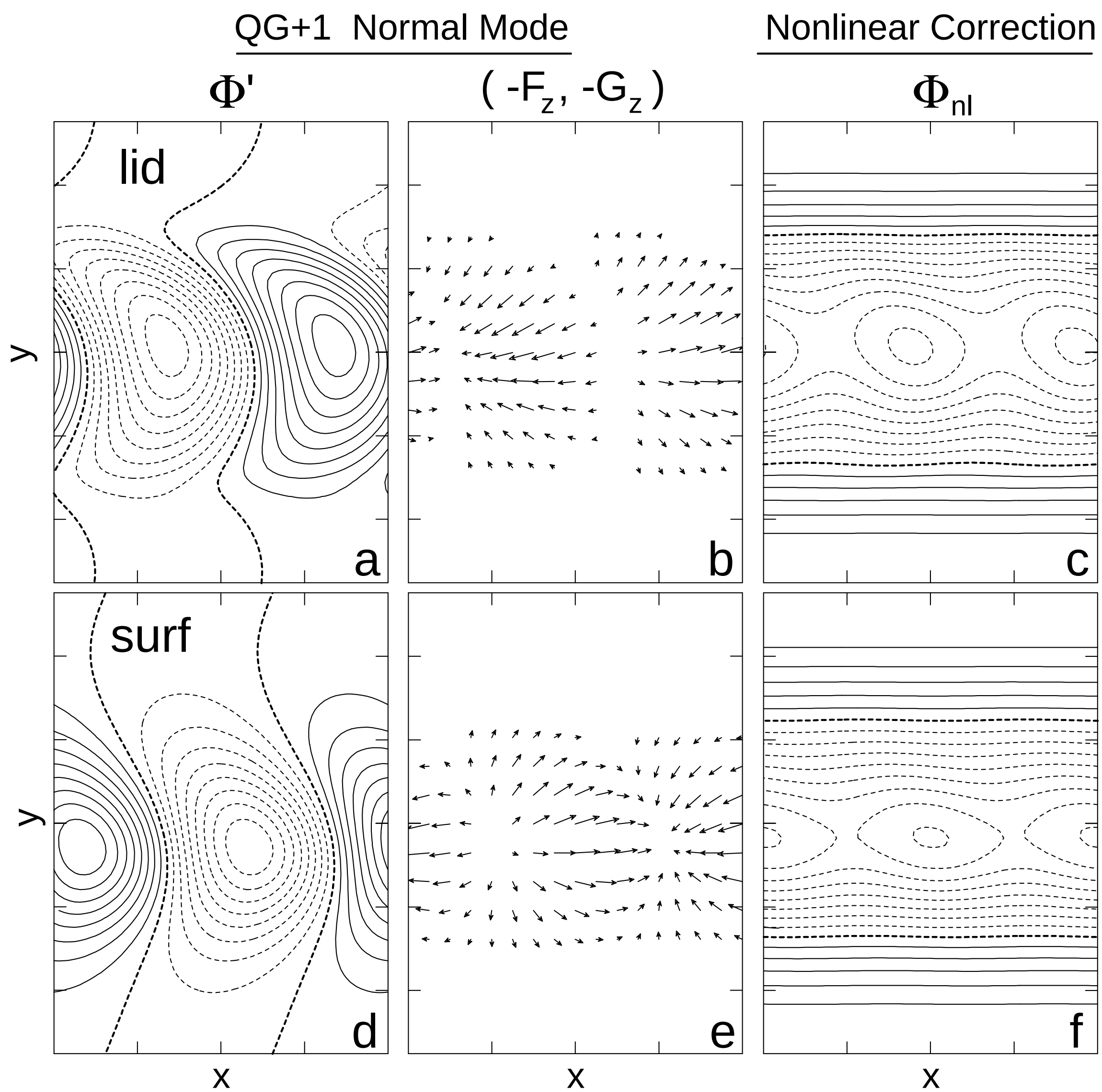


Baroclinic Asymmetry I

Initial Time ($t = 0$)

- ▷ ageostrophic winds $\rightarrow$ frontogenesis
- ▷ nonlinear PV inversion $\rightarrow$ cyclonic shear

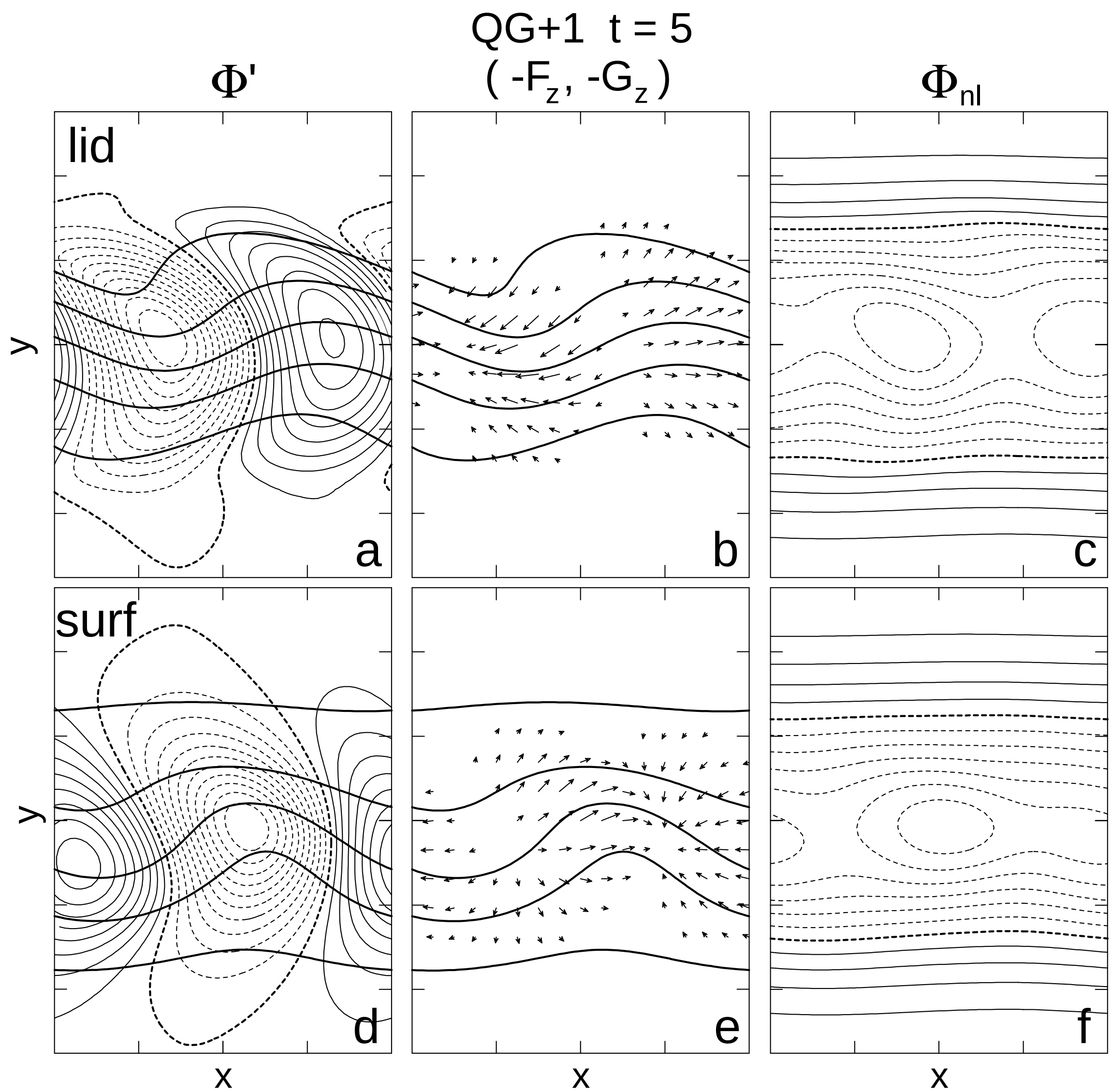
Snyder et.al. (1991), Nakamura (1993)



Baroclinic Asymmetry II

Finite Amplitude ($t = 5$)

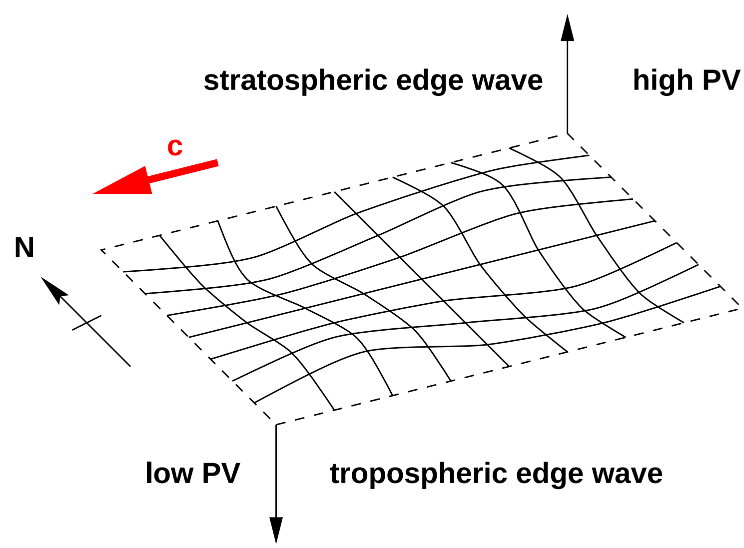
- ▷ cumulative asymmetry in Φ
- ▷ ageostrophic winds $\rightarrow$ frontogenesis
- ▷ nonlinear PV inversion $\rightarrow$ cyclonic shear



Tropopause Modelling

Waves on the Tropopause

- ▷ tropopause interface between high/low PV fluids
- ▷ QG: Rivest et al (92); Juckes (94); Held et al (95)
- ▷ vertical decay away from tropopause
- ▷ laterally-periodic, travelling wave solution



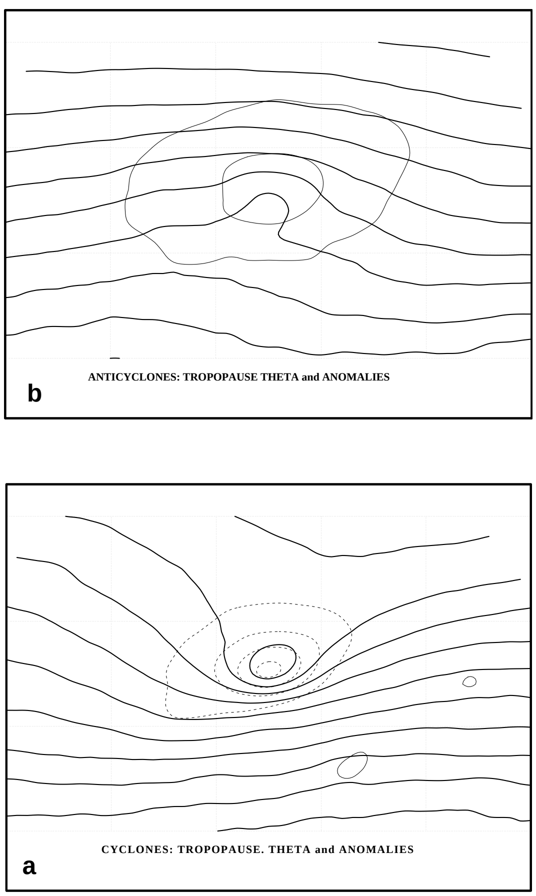
Dynamical Asymmetry

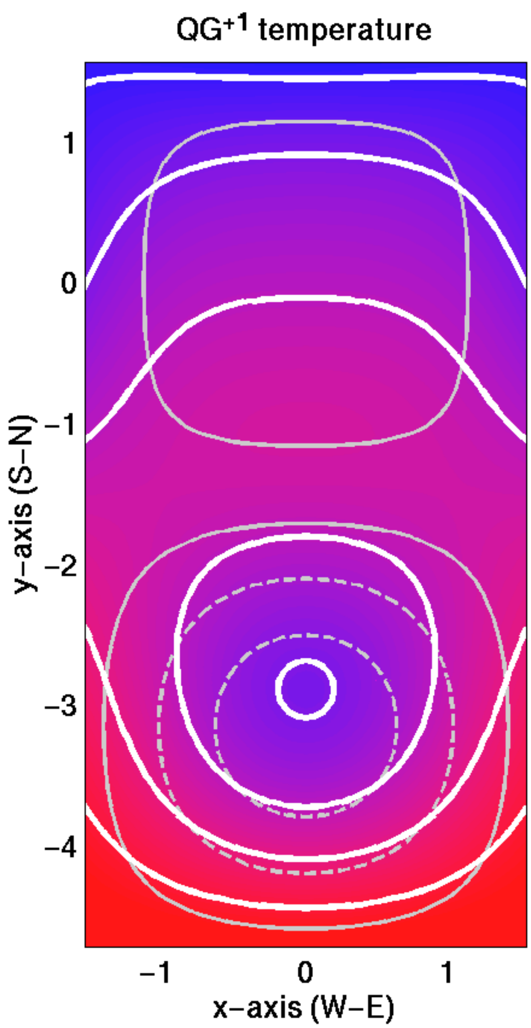
- ▷ QG edge waves are low/high symmetric
- ▷ characterize asymmetry at QG^{+1}

Tropopause Map I

Tropopause Temperature & Anomaly

- composite observations: high & low
- QG+1 wave: temperature contours
- strong bull's-eye low vs weak square-wave high



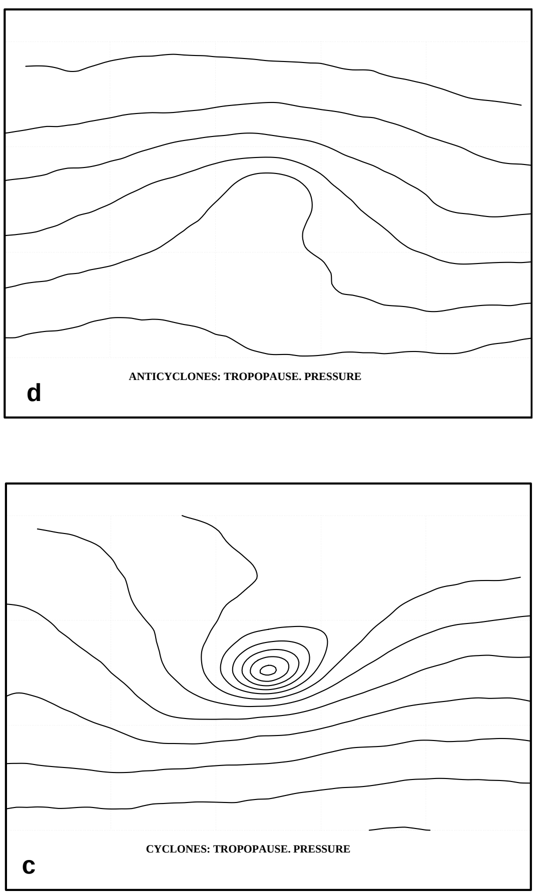


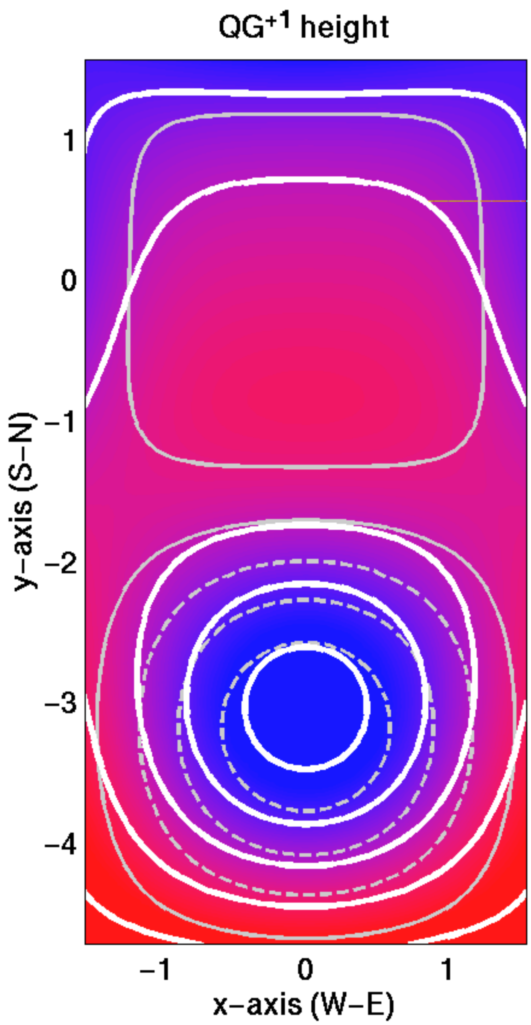
- high/low wave amplitudes: dynamically correlated
- composite amplitudes: top quartile of highs & lows

Tropopause Map II

Tropopause Height/Pressure

- composite observations: height contours
- QG+1 wave: pressure & anomaly contours
- strong bull's-eye low vs weak square-wave high





- includes N-S tilt of mean tropopause

Zonal Profile

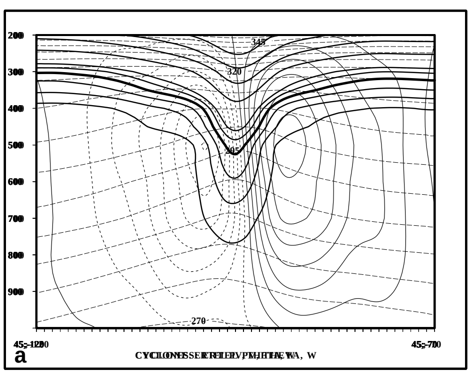
PV, Temperature & Vertical Motion

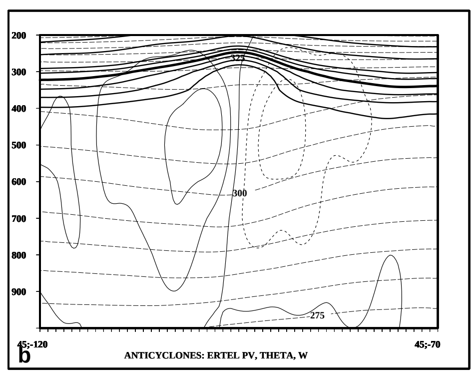
- ▷ tropopause interface

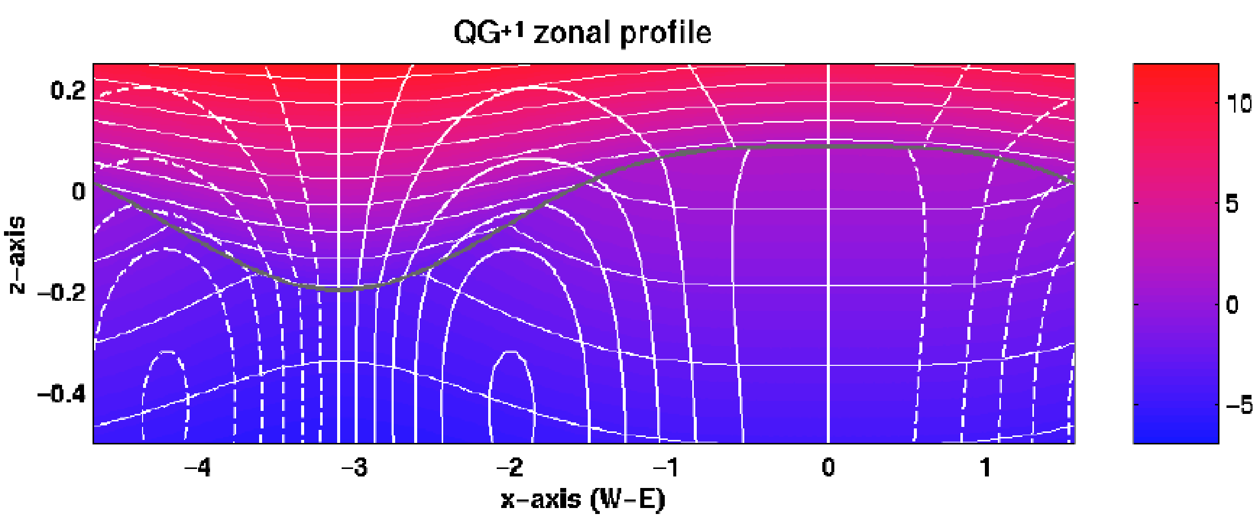
  → enhanced downward displacement for cyclone
- ▷ potential temperature contours

  → peaked disturbance for cyclone
- ▷ vertical motion

  → localized dipole structure for cyclone







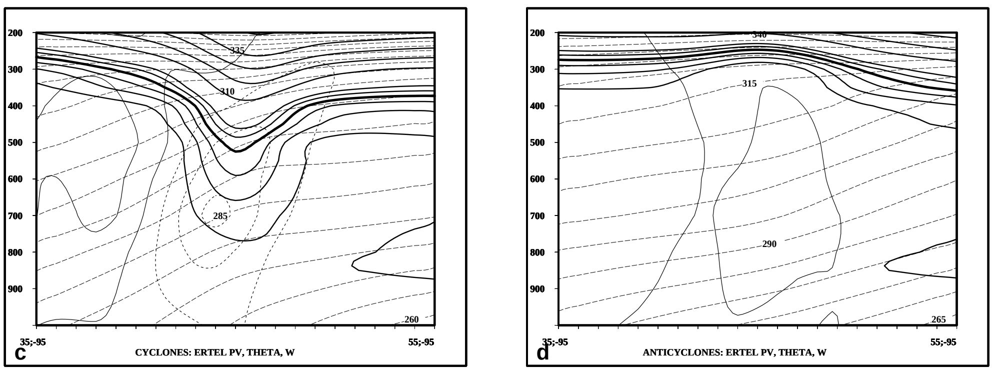
Meridional Profile

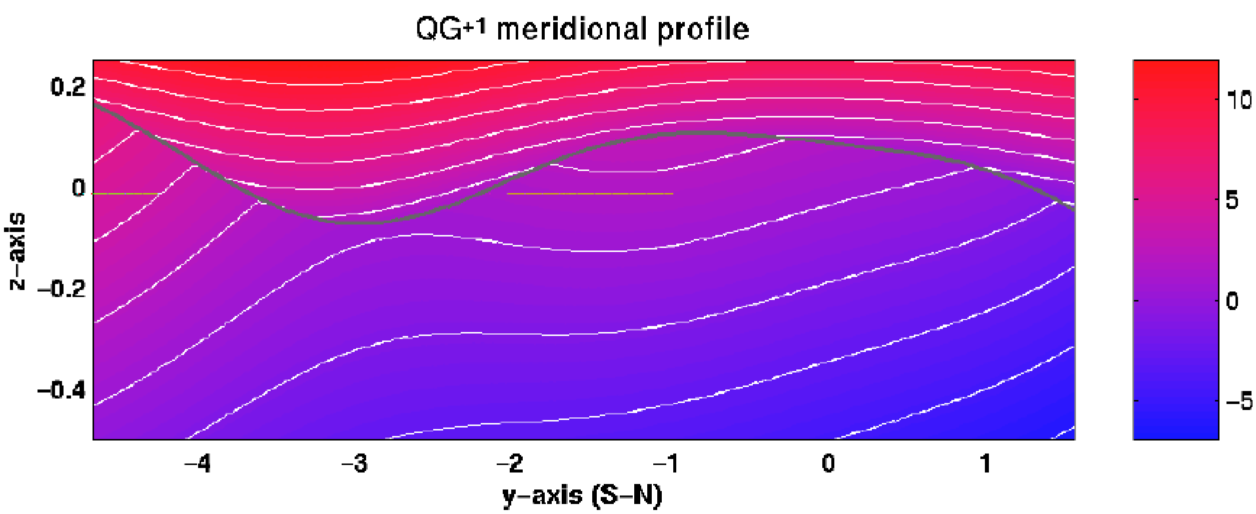
Meridional PV & Temperature

- ▷ tropopause interface

  → enhanced downward displacement for cyclone

  → steepest gradient on equatorward edge of low



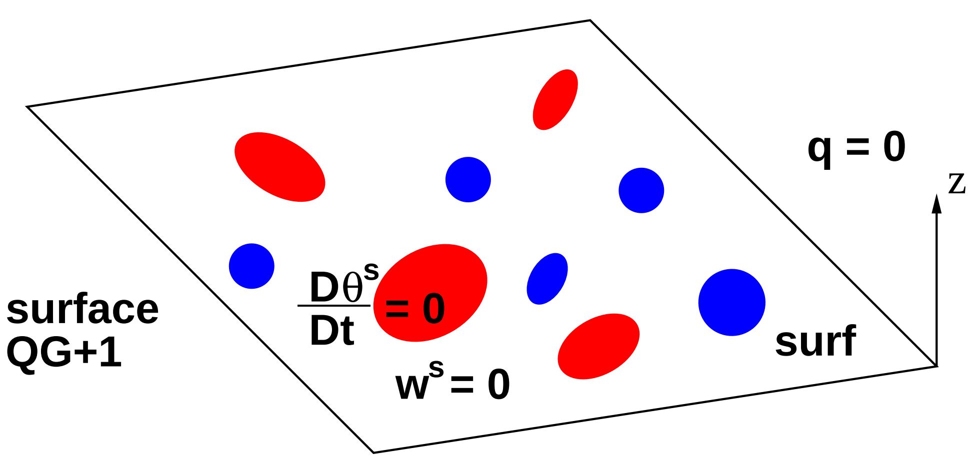


Turbulent Organization of Vortices

> "Evidently, the organization and growth of the system out of the small-scale chaos of the vorticity field is the most important process."
>
> Sanders (1988), on trough development

sQG+1 Dynamics

- ▷ temperature dynamics on a rigid surface, $w^s = 0$
- ▷ sQG+1 dynamics also computationally 2D
- ▷ cyclonic bias from unbiased random vorticity
  - intense, localized cyclones
  - weak, broad anticyclones
- ▷ 2D shallow water & 3D balance equation turbulence
  - weak anticyclonic bias at small Rossby numbers



sQG+ Analysis

Perturbative Inversion

- zero PV ($q = 0$) and θ^s determine potentials

$$\begin{aligned} \Phi &= \Phi^0 + \mathcal{R}\,\Phi^1 + \ldots \\ F &= \mathcal{R}\,F^1 + \ldots \\ G &= \mathcal{R}\,G^1 + \ldots \end{aligned}$$

- QG: Laplace inversion for Φ^0 (computationally 2D)

$$\nabla^2\,\Phi^0 = 0 \quad ; \quad (\Phi_z)^s = \theta^s$$

- QG+1: Poisson inversions at next-order

$$\begin{aligned} \nabla^2\,\Phi^1 &= |\nabla\,\Phi_z^0|^2 & ; \quad (\Phi_z^1)^s = 0 \\ \nabla^2\,F^1 &= 2\,J(\Phi_z^0, \Phi_x^0) & ; \quad (F^1)^s = 0 \\ \nabla^2\,G^1 &= 2\,J(\Phi_z^0, \Phi_y^0) & ; \quad (G^1)^s = 0 \end{aligned}$$

- QG+1: exact Poisson solutions

$$\begin{aligned} \Phi^1 &= \frac{1}{2}\,(\Phi_z^0)^2 + \tilde{\Phi}^1 \\ F^1 &= \Phi_y^0\,\Phi_z^0 + \tilde{F}^1 \\ G^1 &= -\Phi_x^0\,\Phi_z^0 + \tilde{G}^1 \end{aligned}$$

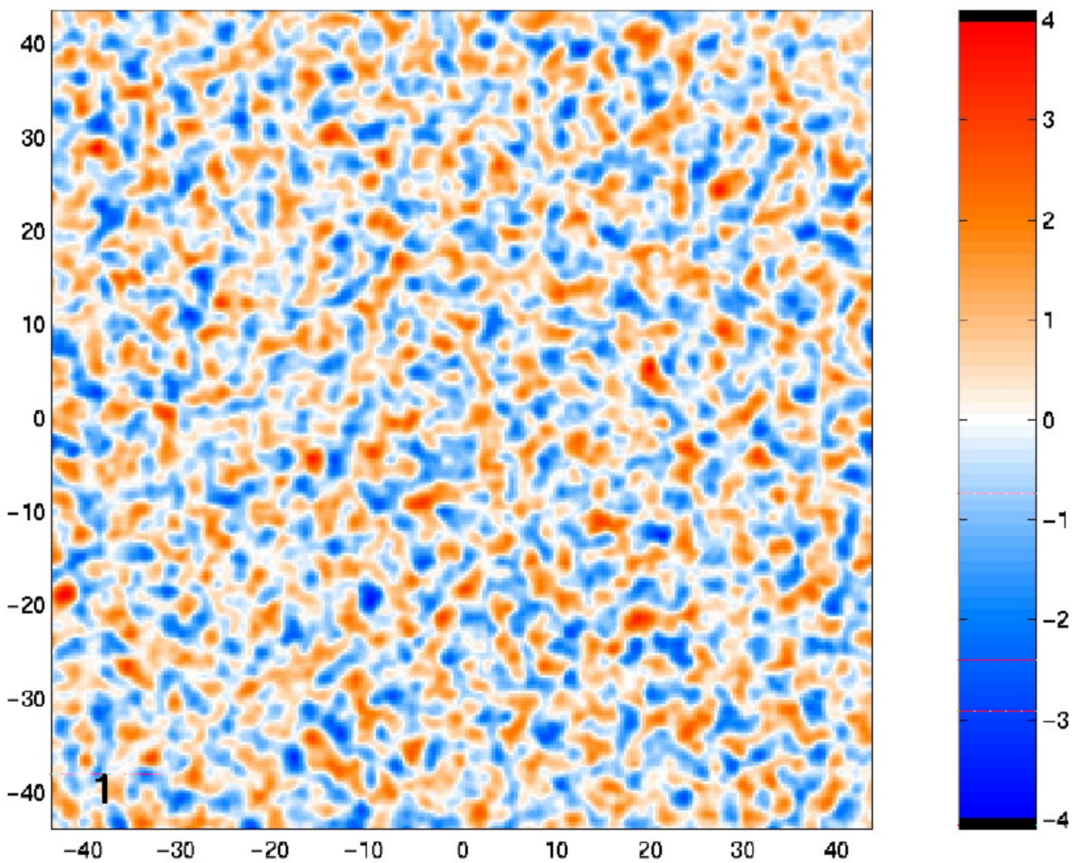
- QG+1: Laplace inversions for $\tilde{\Phi}^1, \tilde{F}^1, \tilde{G}^1$!
- surface advection using QG+1 winds

$$\theta_t^s + (u^0 + \mathcal{R}\,u^1)\,\theta_x^s + (v^0 + \mathcal{R}\,v^1)\,\theta_y^s = 0$$

Random Vorticity

Symmetric Initial Condition

- ▷ potential temperature on surface
- ▷ peaked energy spectrum (Polvani, et.al. 1994)
- ▷ large domain size



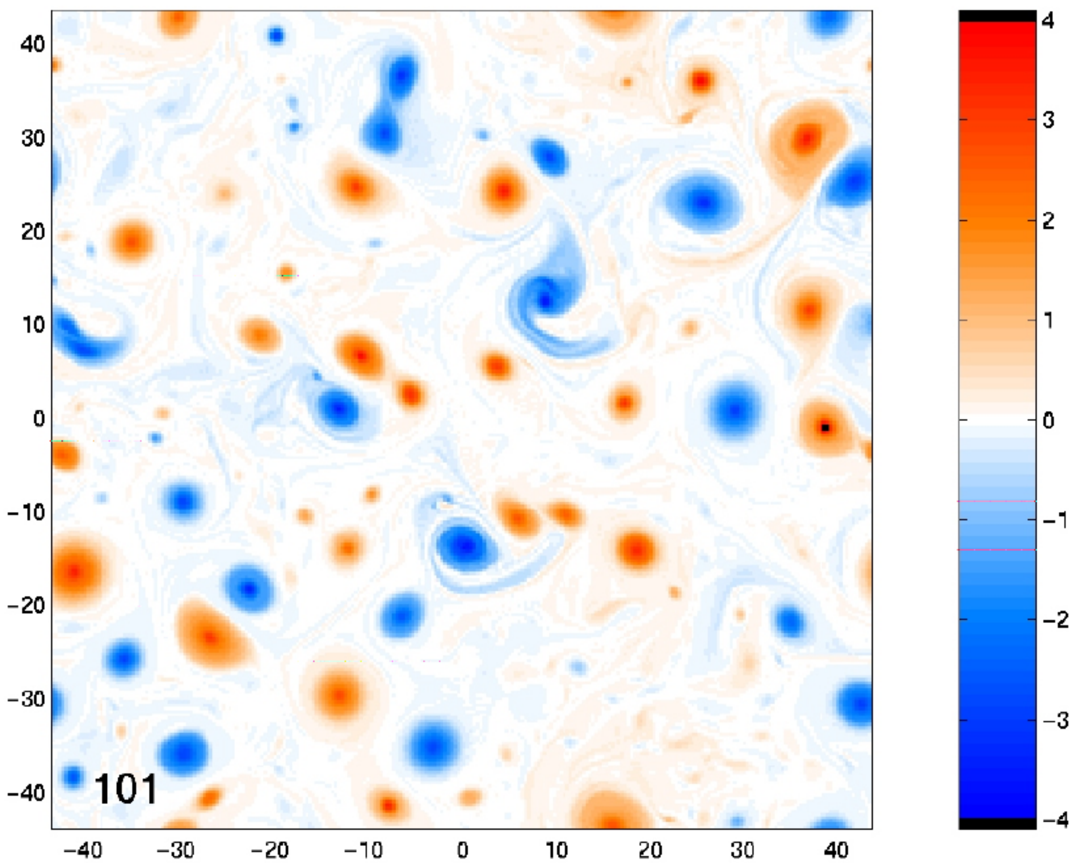
Computations

- ▷ pseudo-spectral with de-aliasing
- ▷ weak ∇^8 hyperdiffusion

sQG Dynamics

Symmetric Organization

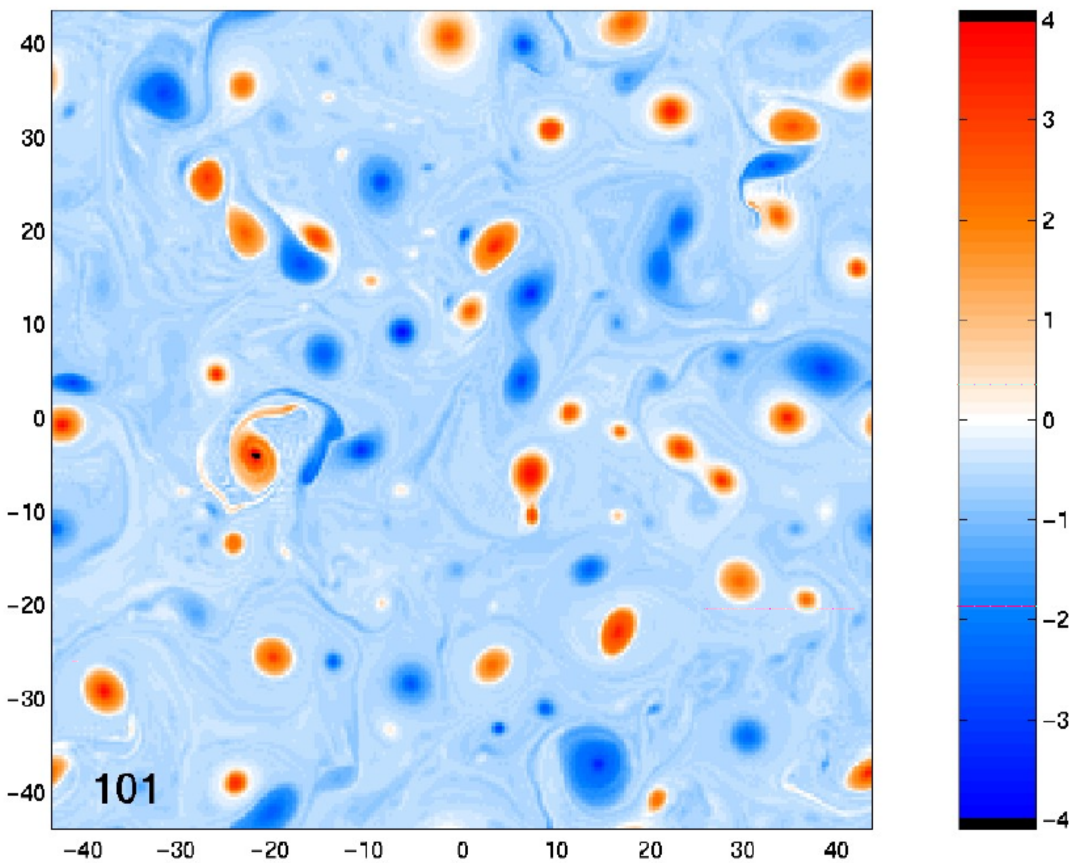
- organization to large vortices (mergers)
- dissipation of thin filaments



sQG+1 Dynamics

Asymmetric Organization

- ▷ surface cooling (blue background)
- ▷ cyclones are more localized & intense



sQG+1 Asymmetry I

Distributions

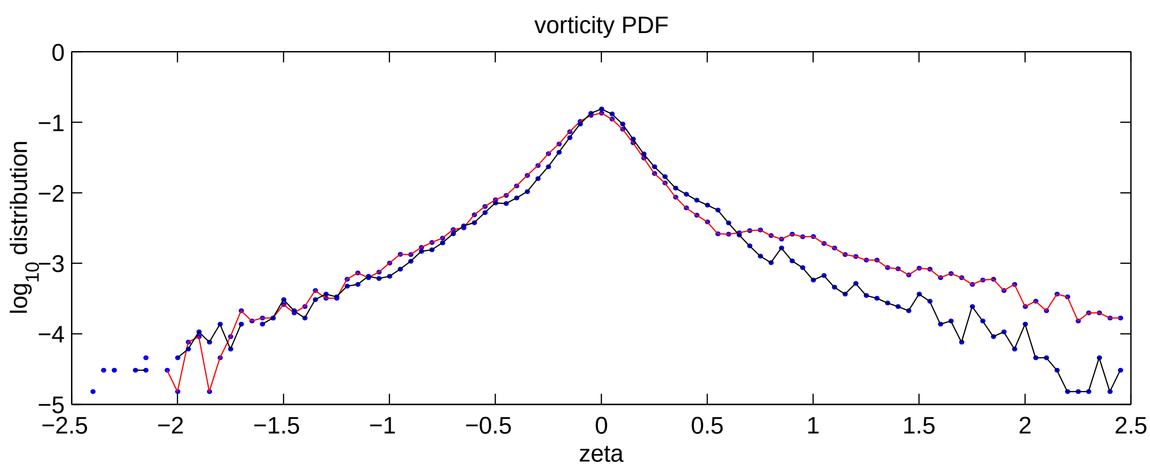
- ▷ increase in extreme cyclonic vorticity

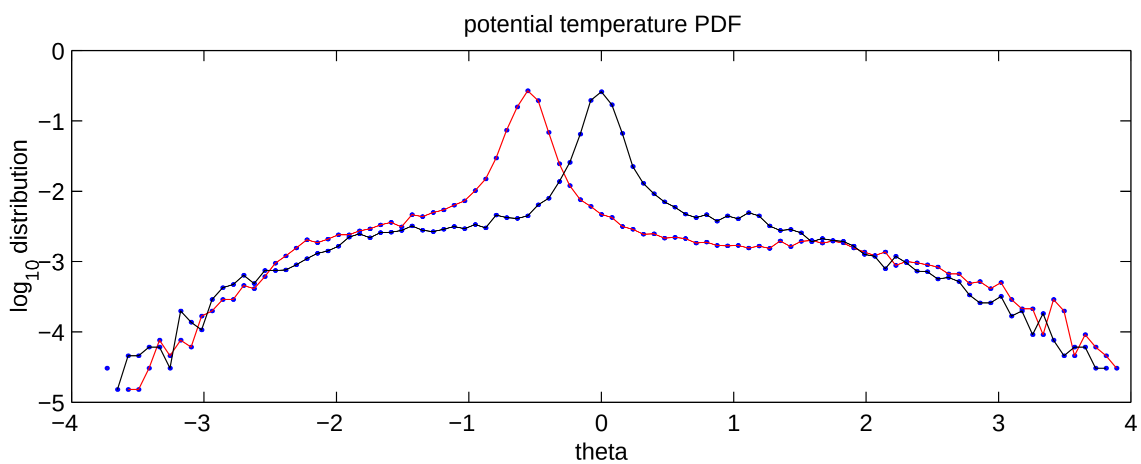
  more intense cyclones

- ▷ blue-shift of potential temperature peak

  surface cooling

- ▷ little change in potential temperature tails
- ▷ one evolution, need statistical ensembles





sQG+1 Ensemble Asymmetry

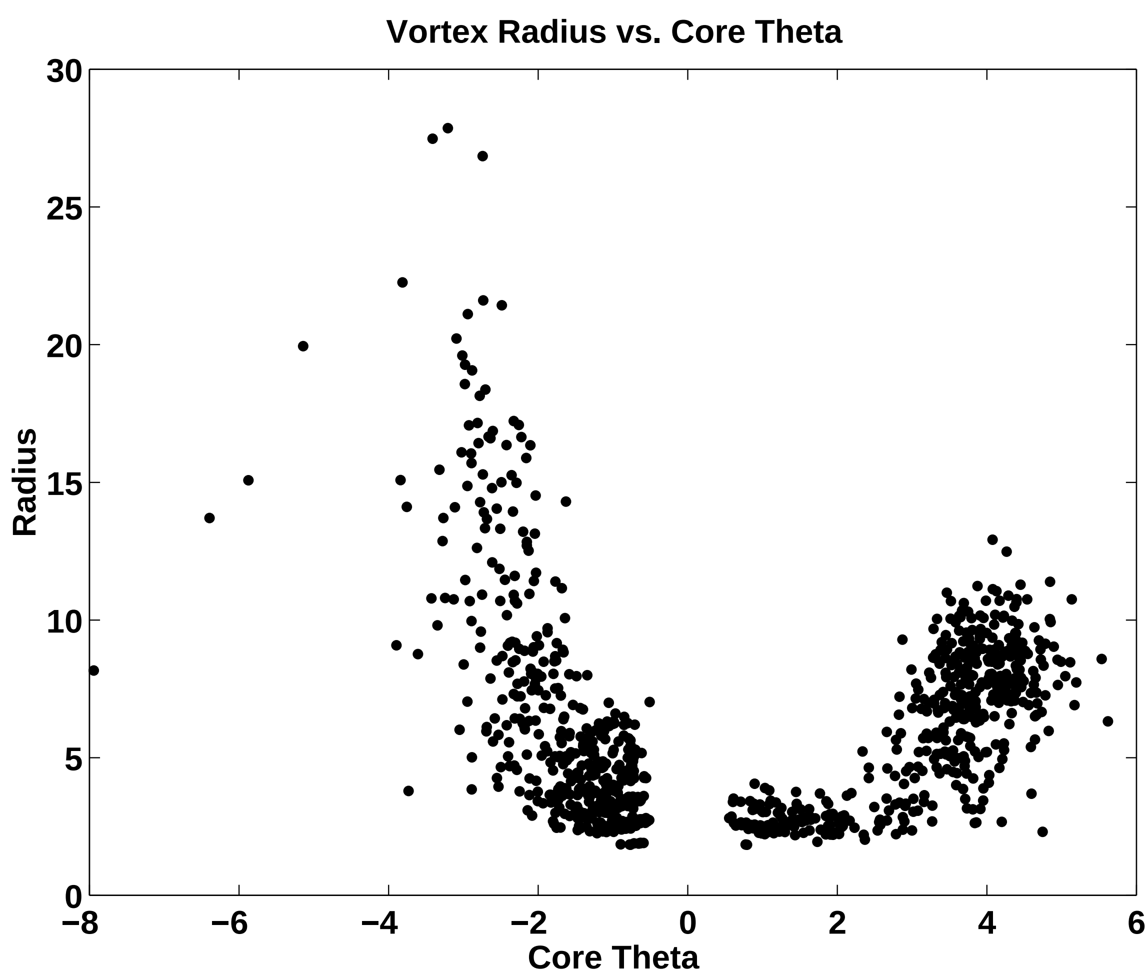
Vortex Structure Asymmetry

- ▷ structural asymmetries of cyclones/anticyclones

  localized, intense cyclones

  broad, weak anticyclones

- ▷ fluid dynamical mechanism: <u>frontogenesis</u>



sQG+1 Asymmetry II

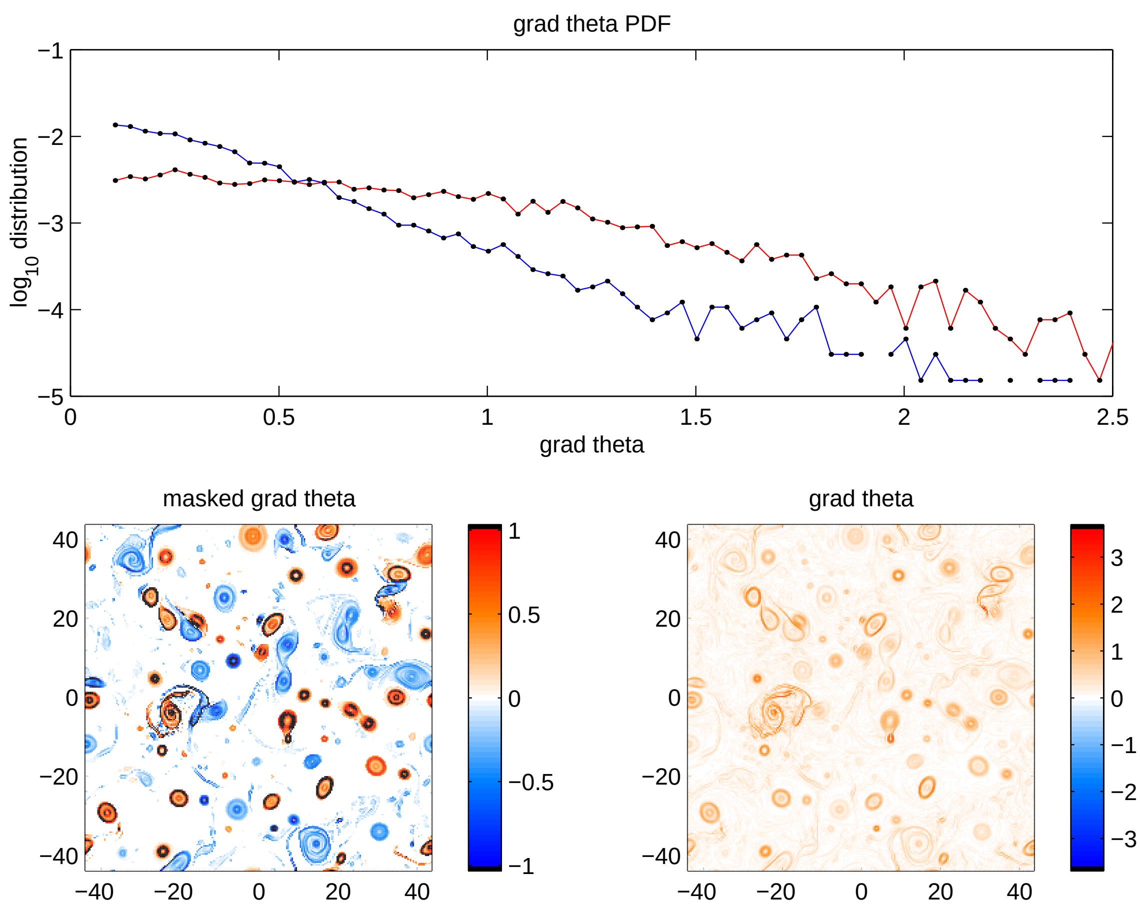
Gradient Distributions

- structural asymmetries of cyclones/anticyclones

  more localized cyclones

  steeper-edged cyclones

- fluid dynamical mechanism: <u>frontogenesis</u>



Vortex Organizations

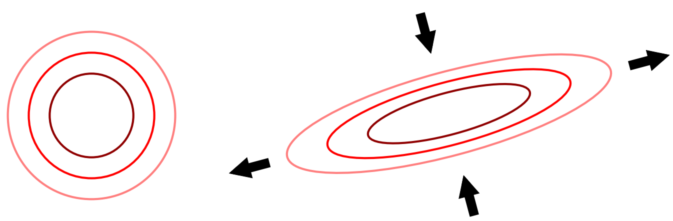
sQG Dynamics

- ▷ dynamics of interactions

  growth of vortices via mergers

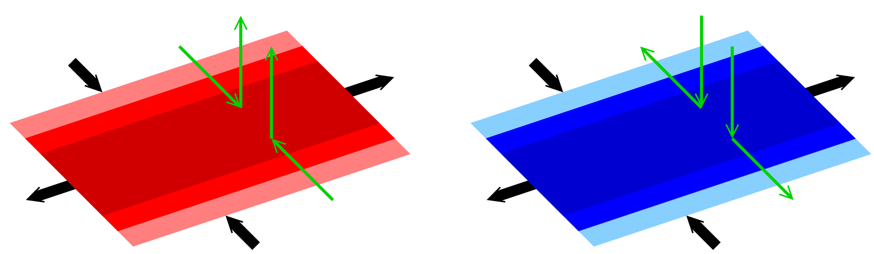
  dissipation via filamentation

- ▷ deformations increase θ-gradients



sQG+1 Dynamics

- ▷ w-induced, ageostrophic motions in strained filaments



- ▷ warm strip convergence vs cold strip divergence

  $\longrightarrow$ surface cooling via frontogenesis

- ▷ non-divergent correction from next-order PV inversion

Mechanisms for Asymmetry

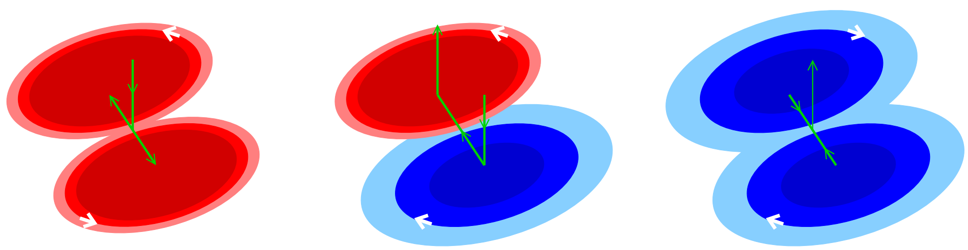
Asymmetric Processes?

- irreversible sQG processes → cumulative divergent effects
- straining of filaments

  warm filaments: rapid dissipation

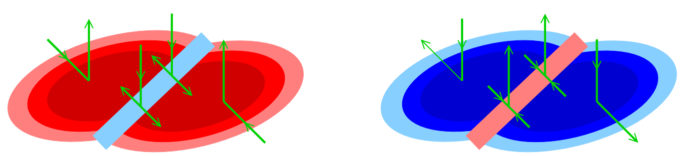
  cold filaments: background cooling

- asymmetric filamentation by vortex interactions

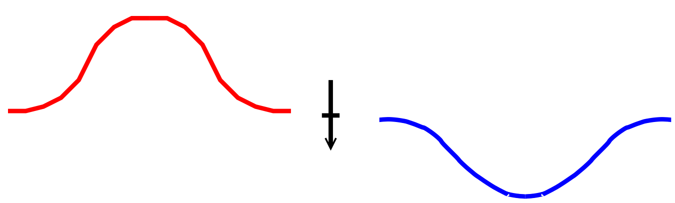


cyclone retraction vs anticyclone extension

- vortex mergers & severe encounters (?)



cyclonic steepening vs anticyclonic spreading



- cyclones: localized, intense, (elliptical)
- anticyclones: broad, weak, (axisymmetric)

Summary

QG+1 Asymmetries

- ▷ baroclinic instability:
  - warm convergence & cold divergence
  - cyclonic enhancement by PV corrections
- ▷ tropopause travelling waves:
  - enhanced downward displacement for cyclones
- ▷ surface vortex organizations:
  - cyclone/anticyclone asymmetry
  - surface cooling & frontogenesis

Future Directions

- ▷ quantification of sQG+1 asymmetric processes
  - vortex interactions
- ▷ vertical influence in vorticity organizations
  - two-surface sQG+1
- ▷ gravity wave generation & interaction