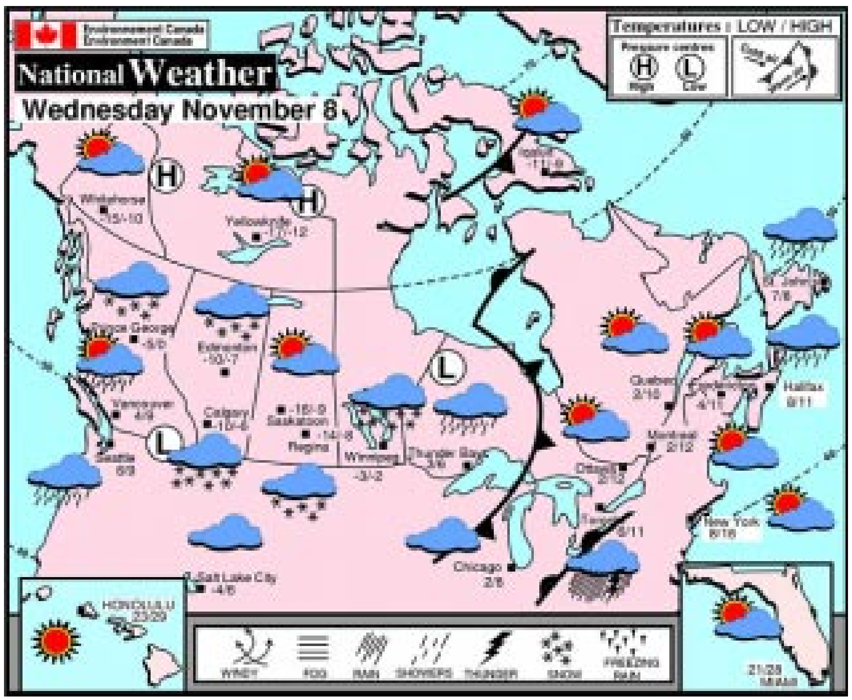
Computational Models for Understanding Weather

Mathematics for Atmospheric Science

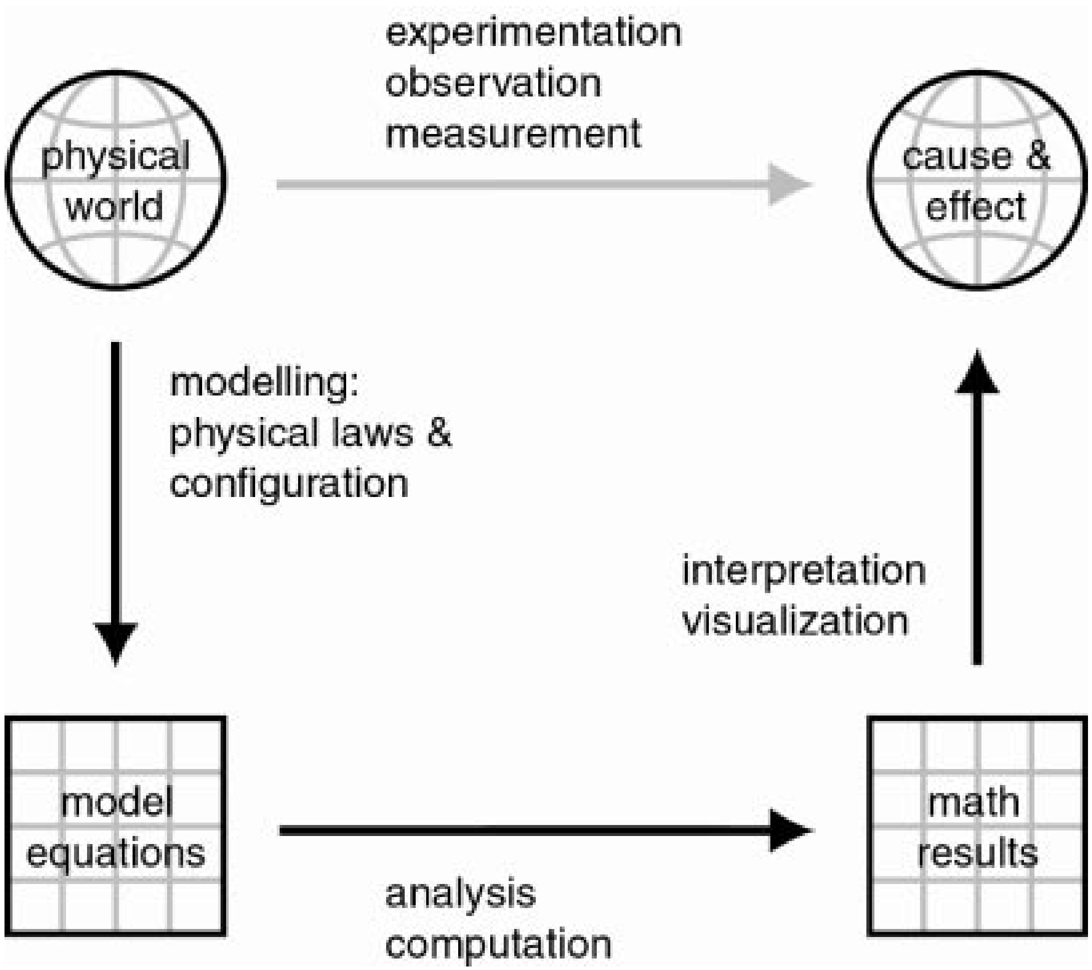


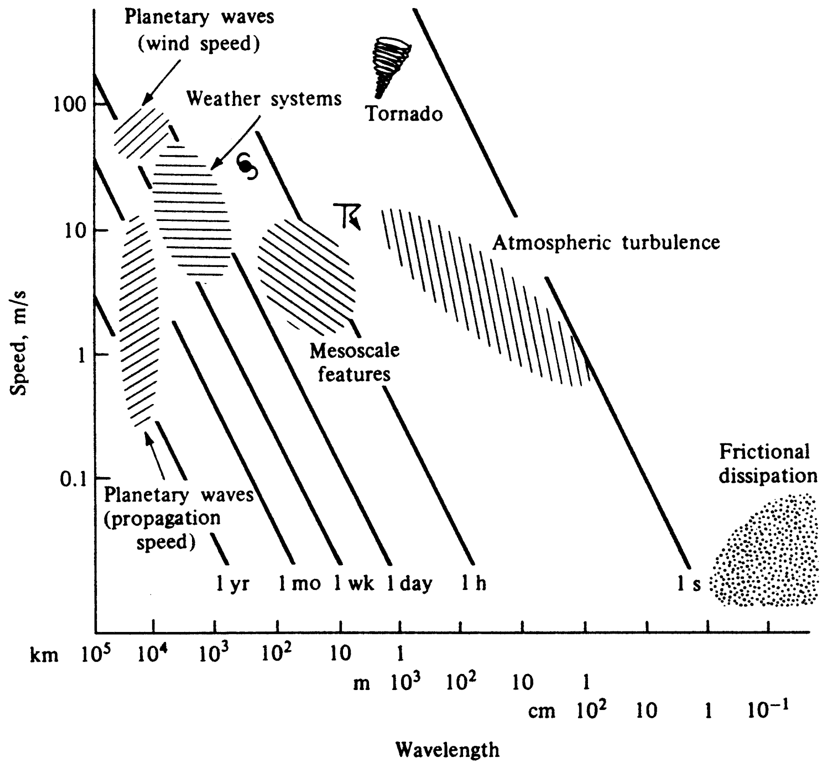
http://weather.ec.gc.ca

- ▷ Chris Snyder, Rich Rotunno (NCAR Boulder)
- ▷ Greg Hakim (Univ of Washington)

Science via Mathematics

A 3-Step Process





Dutton

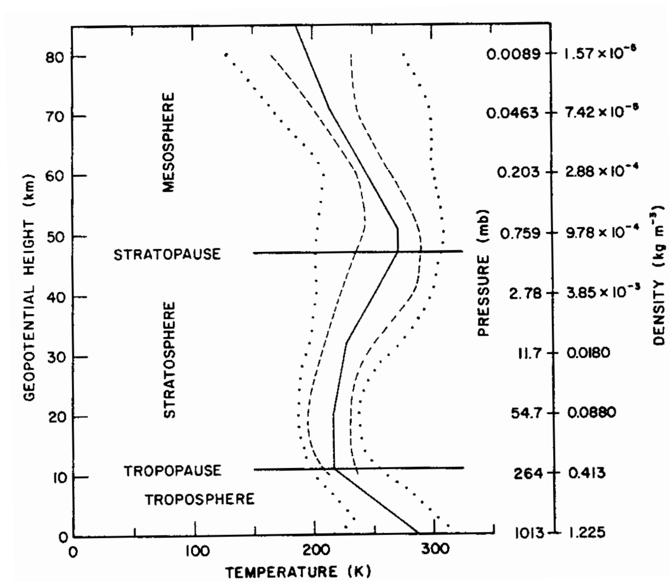
A Matter of Scales

- ▷ climatology: long-term trends (seasons, years)
- ▷ meteorology: short-term forecast (hours, days)

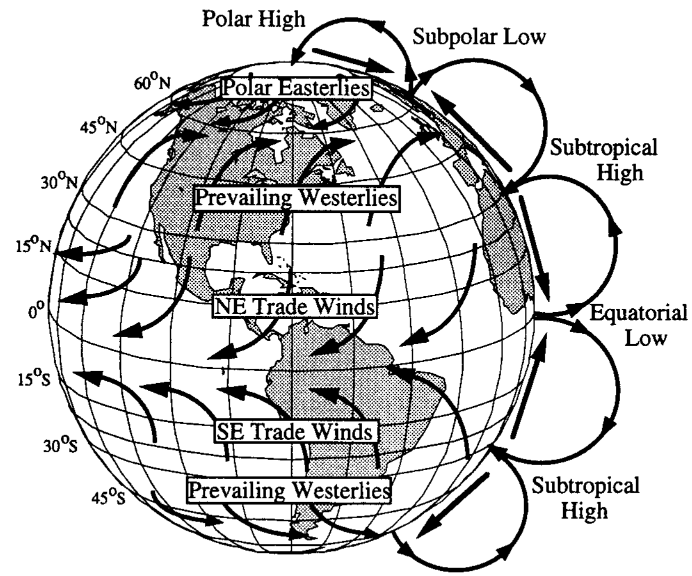
  synoptic (global), mesoscale (continental) & microscale (local)

Atmospheric Structure

A Problem in Three-Dimensions



Gill



Conway

- vertical: troposphere, stratosphere, . . .
- global: tropics, midlatitudes, mountains, polar caps, . . .

A Model for the Midlatitudes

Physical Laws & Configuration

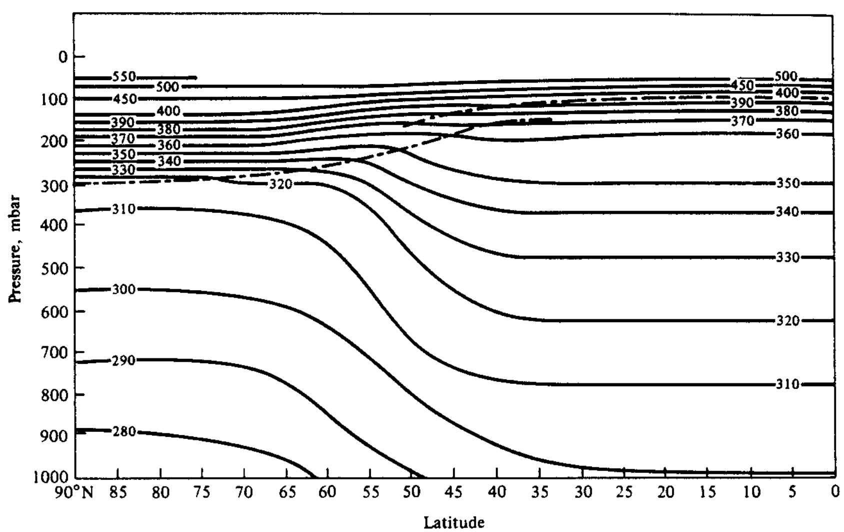
- fluid mechanics (winds & pressure)

  $\longrightarrow$ Coriolis rotation & density stratification

- thermodynamics (potential temperature & pressure)

  $\longrightarrow$ NO humidity/moisture feedbacks

- troposphere: surface & tropopause (alt $\approx$ 10 km)



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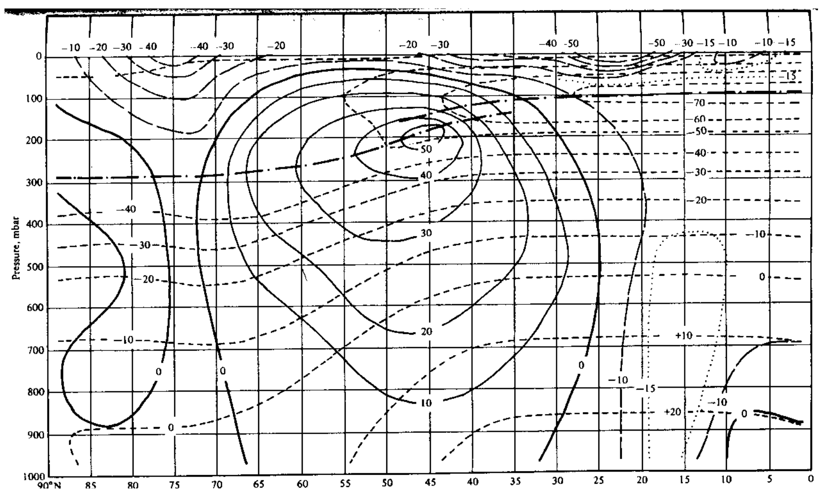
Midlatitude Jetstream

Thermal Wind Balance

- ▷ pole-equator temperature gradient + Coriolis force → jetstream
- ▷ zonal (circumpolar) winds, maximal on tropopause
- ▷ seasonal N-S migration



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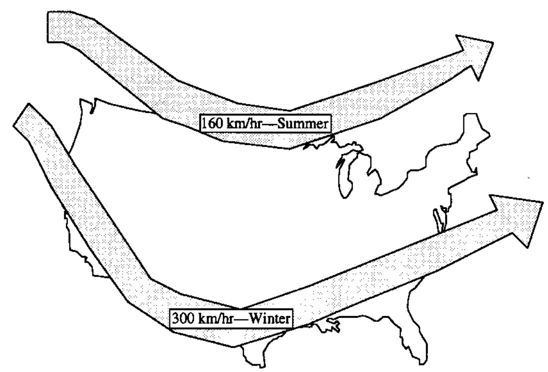


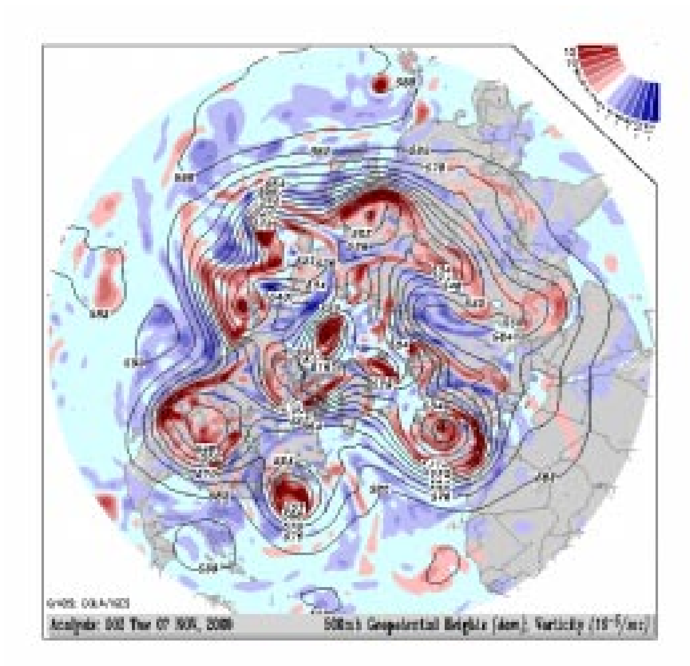
Conway

- ▷ zonal jetstream in unstable → weather

Baroclinic Instability

Vortices in the Jetstream

- pressure variations + Coriolis force ⟶ vortical flows
- low pressures: cyclones (CCW in N hemisphere)
- high pressures: anticyclones (CW in N hemisphere)
- meandering of jetstream around vortices



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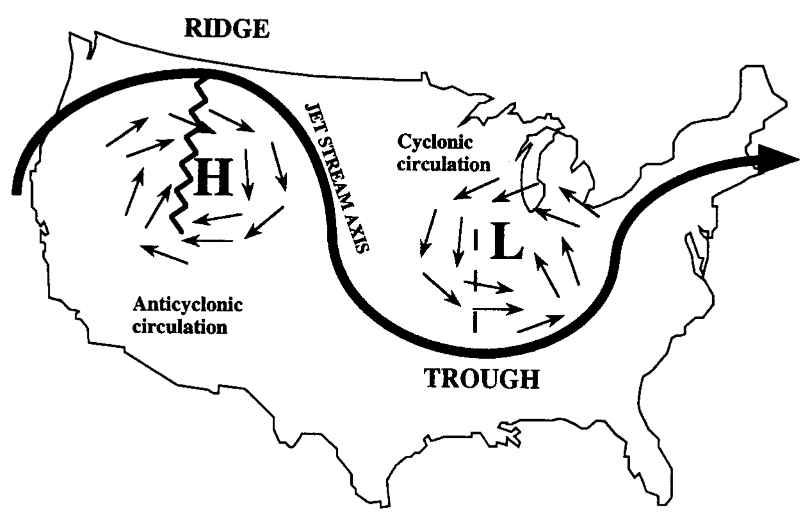


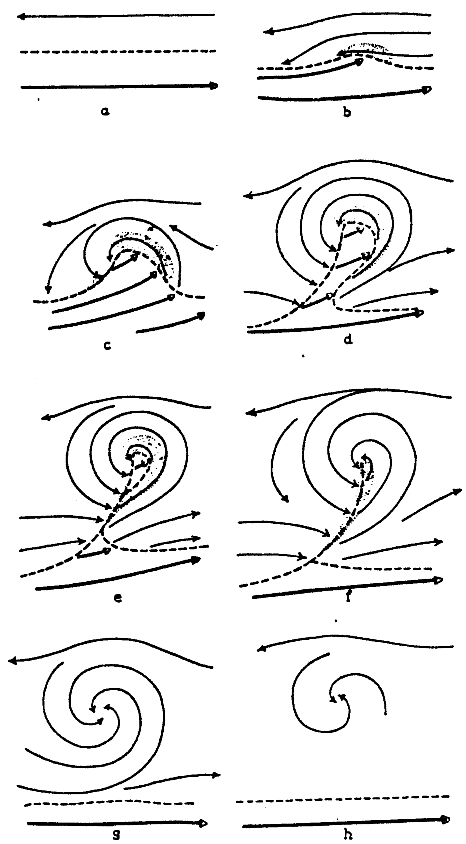
Conway

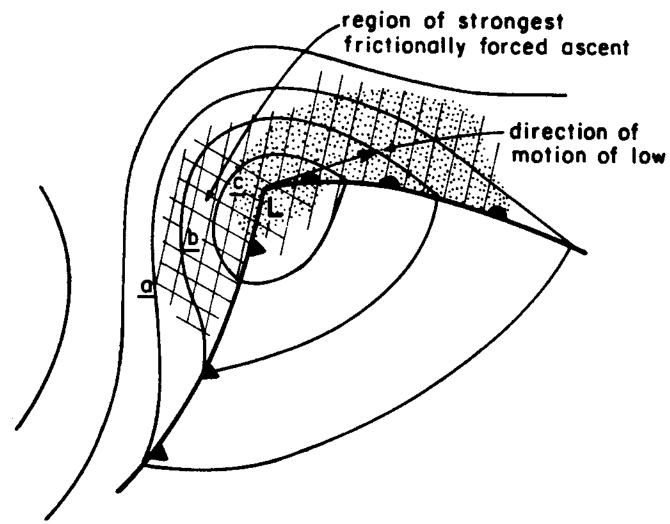
Storm Development

Norwegian Cyclone Model

- ▷ Bjerknes & Solberg (1926): low pressure, cyclonic storm cells

Carlson



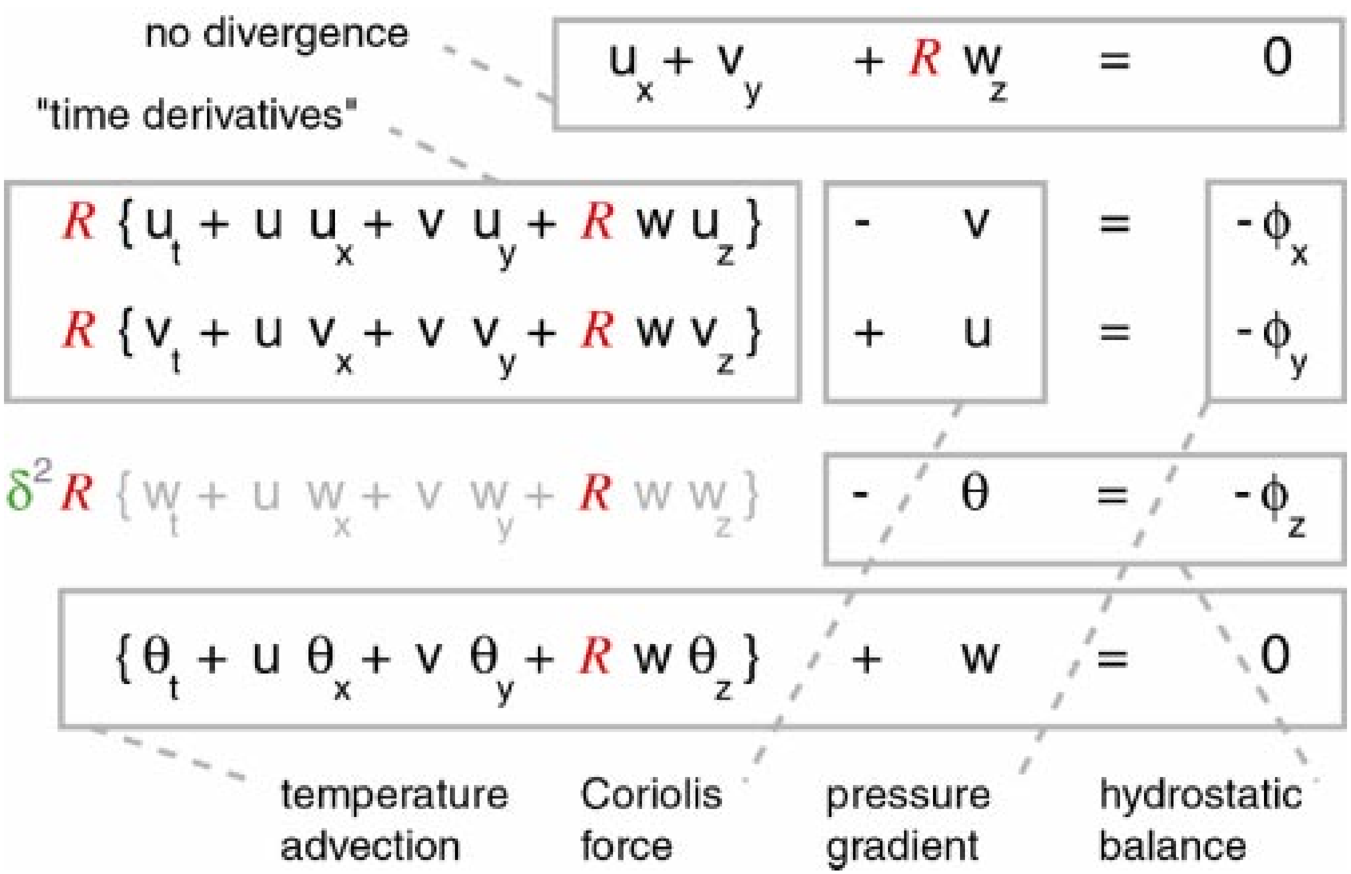


Carlson

Prototypical Model Equations

Geophysical Fluid Dynamics

- Rossby number ($\mathcal{R} \approx 0.1 - 1.0$), hydrostatic limit ($\delta \to 0$)



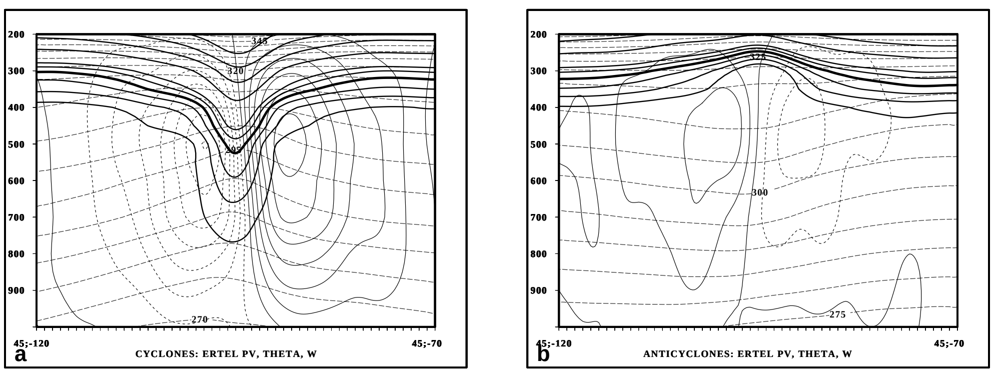
Symmetry-Breaking

Cyclone/Anticyclone Asymmetry

- why do low pressure cells intensify preferentially over highs?
- textbook theory, *quasigeostrophy*, is symmetric ($\mathcal{R}$=0)
- new mathematics: QG^{+1}, small $\mathcal{R}$ perturbation theory

Tropopause Observations

- upper-level troughs as precursors to instability
- troughs from upper-level cyclonic vorticity, Sanders (1988)
- hypothesis: *is the tropopause an organizing level for vorticity?*



Hakim 2000

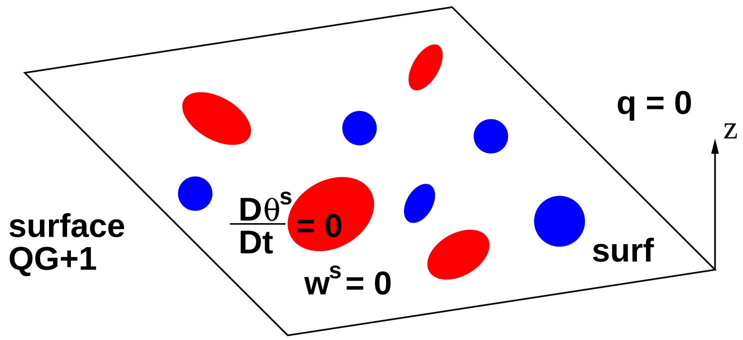
Turbulent Organization of Vortices

> "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

Surface QG^{+1} Dynamics

- new mathematics: sQG^{+1} temperature dynamics on a rigid surface
- cyclonic bias from unbiased random vorticity

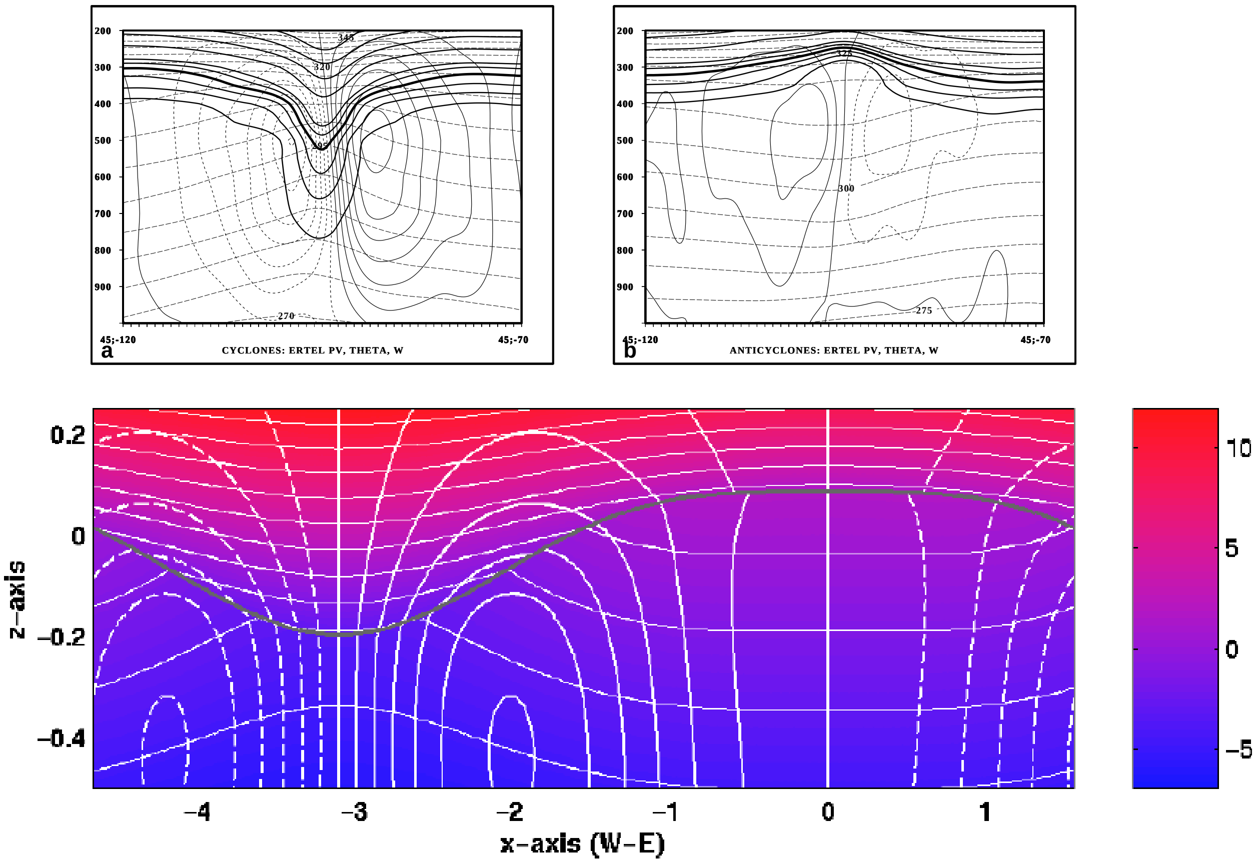
  intense, localized cyclones vs weak, broad anticyclones
- prior models $\longrightarrow$ weak anticyclonic bias at small Rossby numbers!



Tropopause Wave

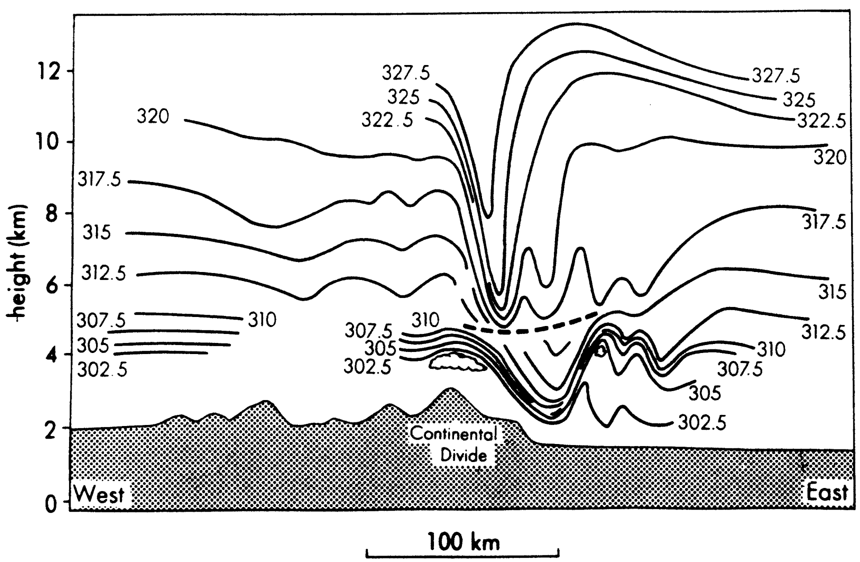
Observations vs Periodic Wave Solution

- ▷ new mathematics: sQG^{+1} tropopause model
- ▷ tropopause interface, potential temperature & vertical motion

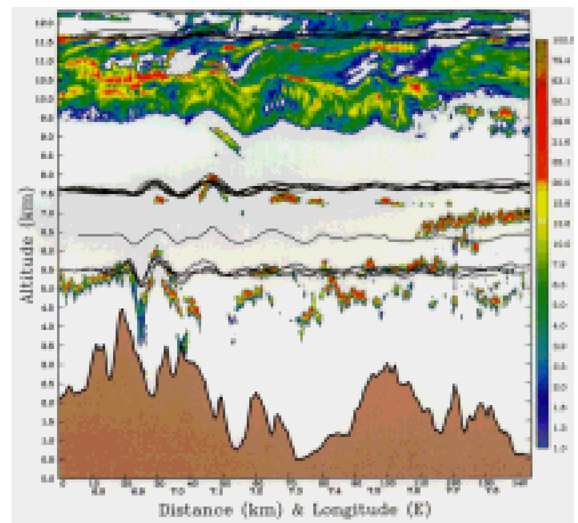


Buoyancy Waves

- ▷ wave response to dense air ascending over a mountain
- ▷ clear air turbulence over alpine regions (Colorado, the Alps)



Atkinson

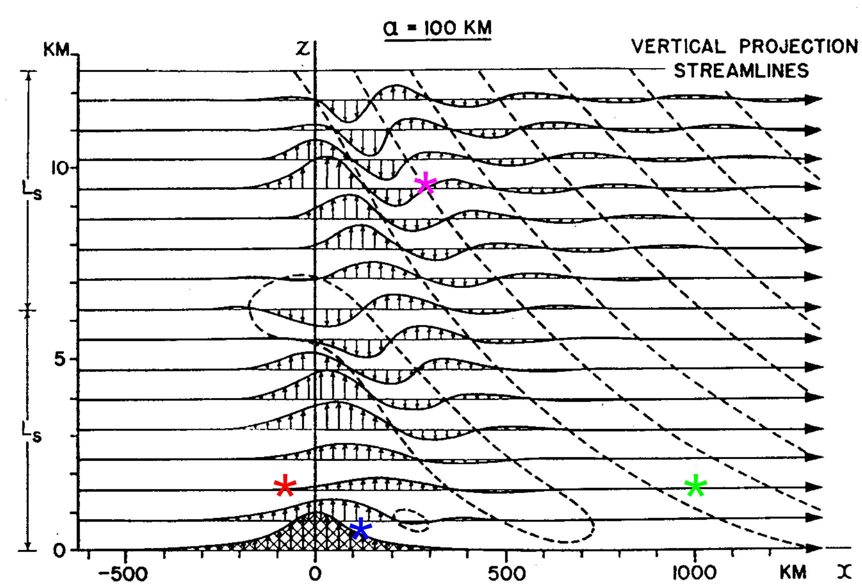


MAP experiment 1999

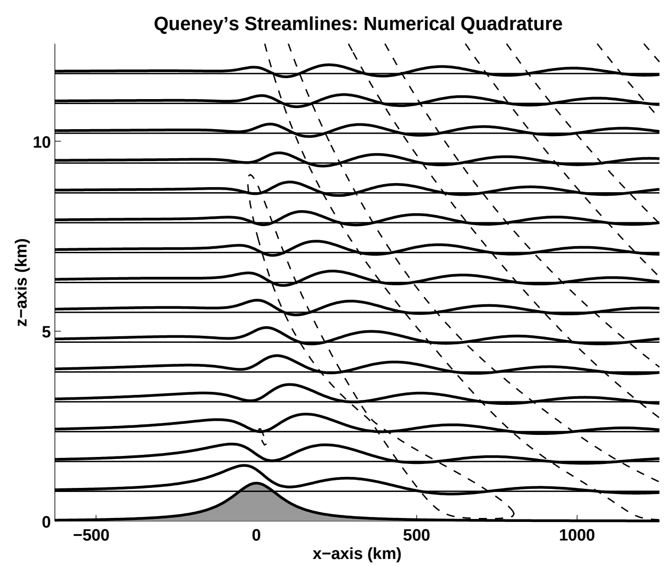
An Old Problem Revisited

Flow over a Mesoscale Ridge

- original work: Queney 1947, *rotating* case ($\mathcal{R}$=1)
- new mathematics: efficient & accurate Fourier quadrature
- adaptable for 3D mountain flow computations



Queney 1947

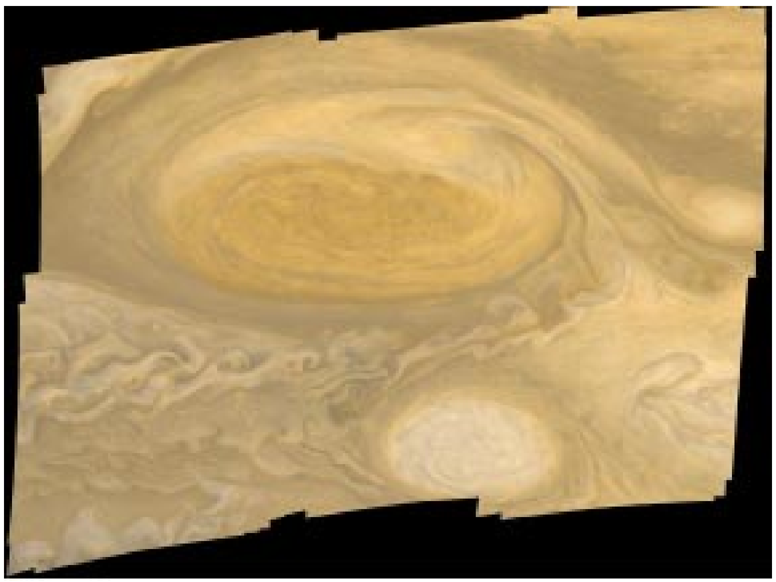


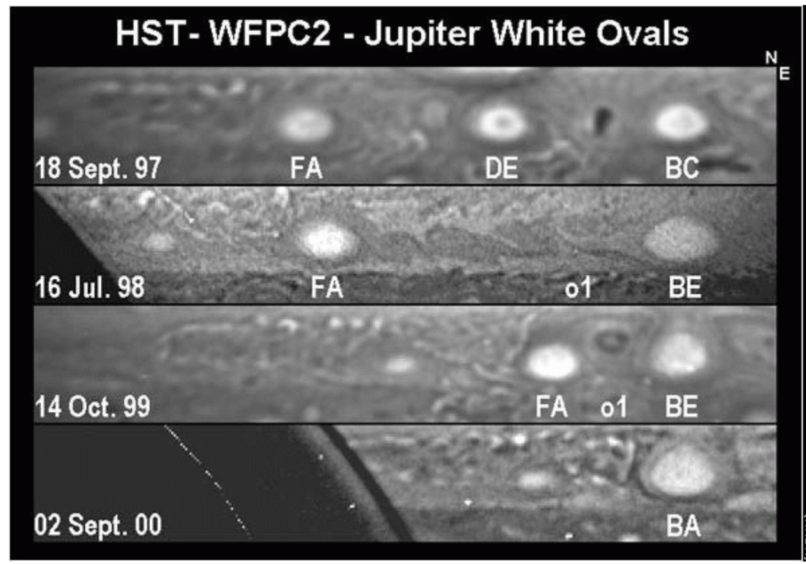
- new direction: nonlinear wave generation

New Frontiers

Jovian Weather

- ▷ vorticity dynamics: filamentation & vortex merger





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