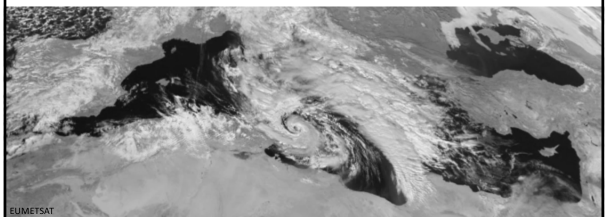
Orographic Cyclogenesis
and the Influence of Mountains on Extratropical Cyclones



Atmos 6250: Mountain Meteorology
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Learning Objectives

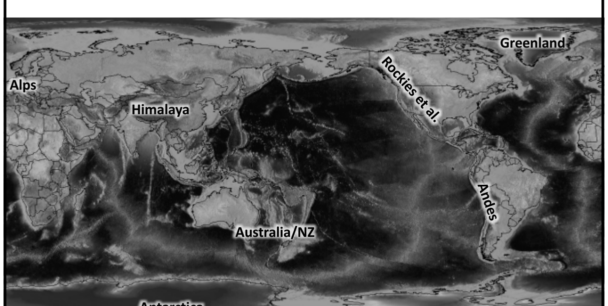
- After this lecture, students will
  - Recognize and understand how mountains affect the climatology and life-cycle of extratropical cyclones
  - Be able to diagnose past, current, and future cyclone evolution in areas of complex terrain
  - Have an improved ability to critically evaluate scientific literature examining orographic cyclogenesis

Outline

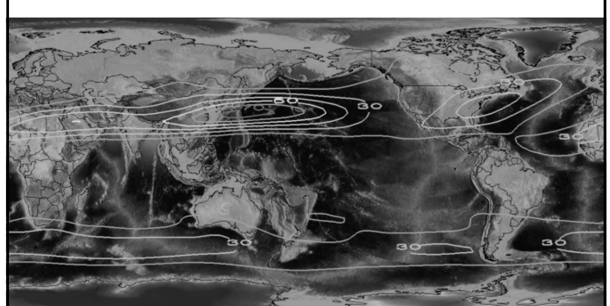
- Climatological Context
- Dynamical Mechanisms
- Alberta Cyclogenesis
- Alpine Lee Cyclogenesis
- Intermountain Cyclogenesis

Climatological Context

Global Topography



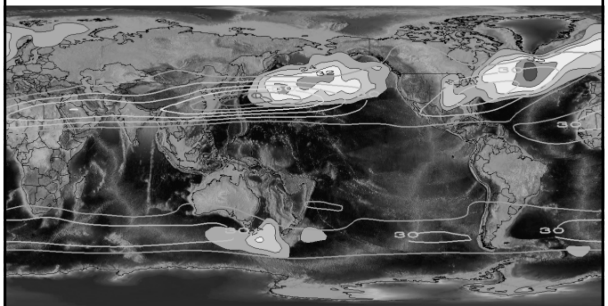
January Climo (1981–2010)



250-mb wind speed

Data Source: NCEP/NCAR Reanalysis, ESRL

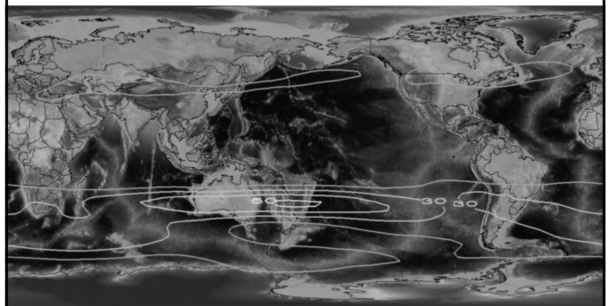
January Climo (1981–2010)



250-mb wind speed and 850-mb transient meridional momentum flux

Data Source: NCEP/NCAR Reanalysis, ESRL

July climo (1981–2010)



250-mb wind speed

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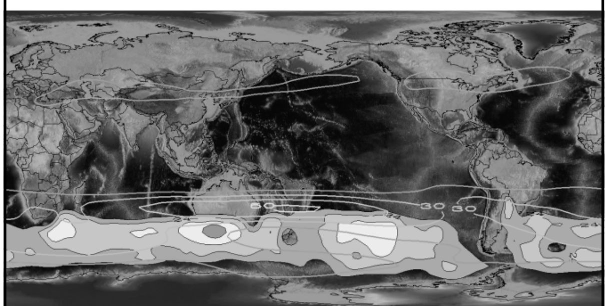
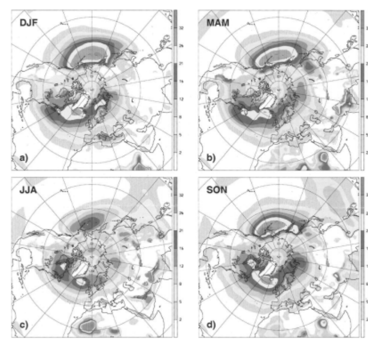
July climo (1981–2010)



250-mb wind speed and 850-mb transient meridional momentum flux

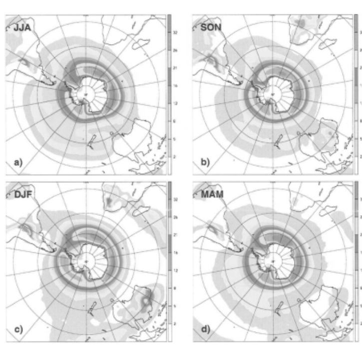
Data Source: NCEP/NCAR Reanalysis, ESRL

NH Cyclone Frequencies (%)



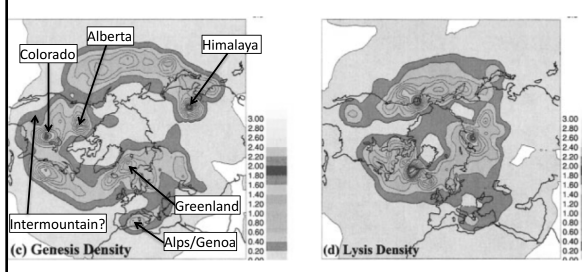
Wernli and Schwierz (2006), ERA-40 1958–2001 (T159 ~125 km interpolated to 1ºx1º)
Statistics for MSLP cyclones

SH Cyclone Frequencies (%)



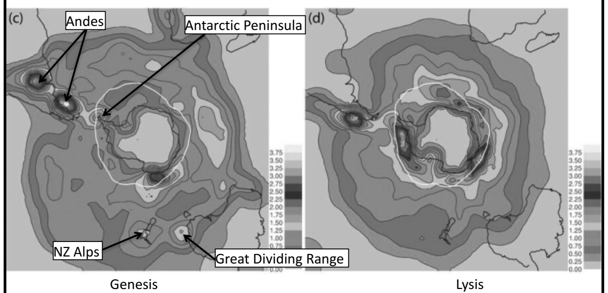
Wernli and Schwierz (2006), ERA-40 1958–2001 (T159 ~125 km interpolated to 1ºx1º)
Statistics for MSLP cyclones

NH Cyclogenesis/Lysis Density



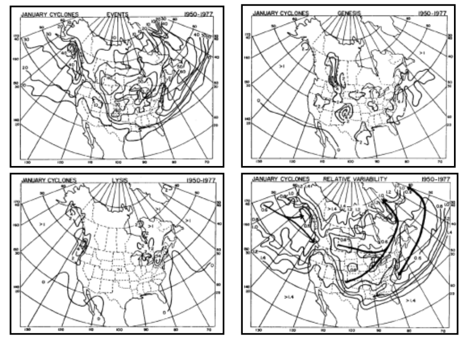
Hoskins and Hodges (2002), ERA-15 & ECMWF Operational Analyses 1979–2000 (T42 ~300 km)
Annual statistics for "feature-tracked" MSLP cyclones

SH Cyclogenesis/Lysis Density



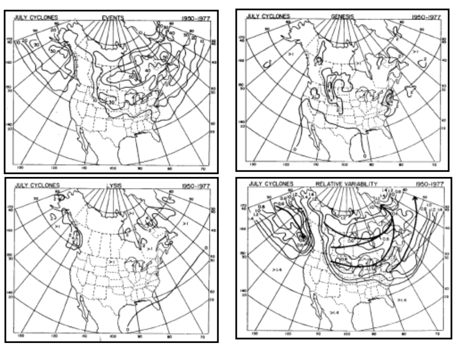
Hoskins and Hodges (2005), ERA-40 1958–2002 (T159 ~125 km)
JJA statistics for ξ_{850} cyclones

January NA Climo



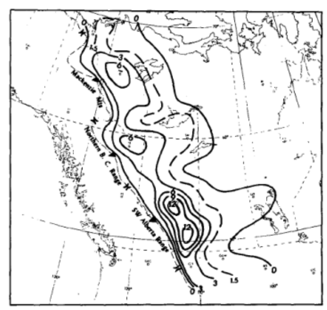
Zishka and Smith (1980), NOAA monthly cyclone track maps 1950–1977

July NA Climo



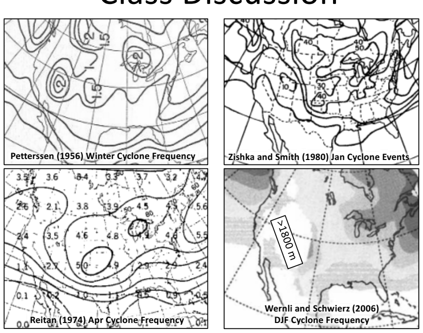
Zishka and Smith (1980), NOAA monthly cyclone track maps 1950–1977

Mesoscale Effects



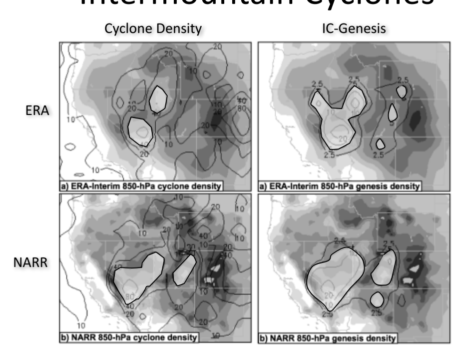
Chung et al. (1976), Cyclogenesis Frequency during 1958

Class Discussion



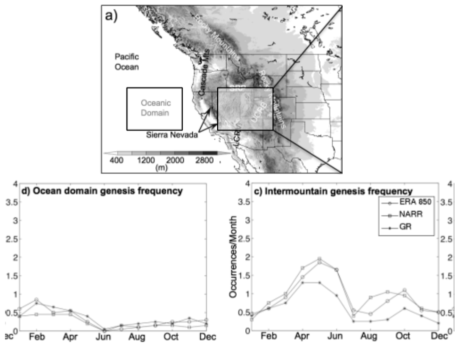
Are Intermountain cyclones a statistical phantom or artifact of MSLP reduction?
How do we explain these disparate results?

Intermountain Cyclones



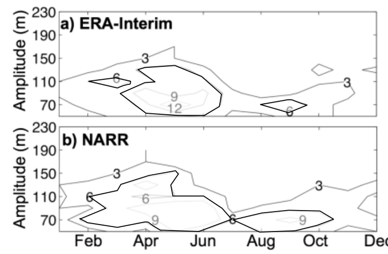
Jeglum et al. (2010)

Seasonality



Jeglum et al. (2010)

Seasonality



Jeglum et al. (2010)

Climate Summary

- Mountains have a profound influence on storm tracks and cyclone statistics
  - Frequent lee cyclogenesis
  - Frequent windward cyclolysis
  - Apparent “discontinuous” or “masked” storm tracks across barriers
- Statistics vary depending on reanalysis characteristics (e.g., grid spacing), identification techniques, and season

Dynamical Mechanisms

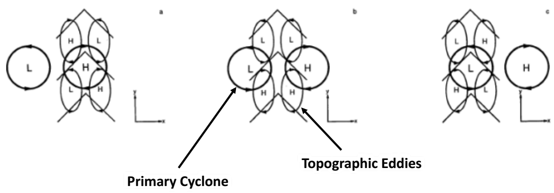
Orography and Cyclones

- Windward column compression contributes to acquisition of anticyclonic absolute vorticity
- Leeward column stretching contributes to acquisition of cyclonic absolute vorticity
- These effects are “superimposed” on the large-scale forcing
  - Best case for lee cyclogenesis is when mountain-induced column stretching occurs in concert with synoptic conditions favorable for cyclogenesis
    - e.g., 500 mb CVA, local maximum in warm advection, condensational heating
  - Almost all cases of lee cyclogenesis are associated with a pre-existing synoptic-scale trough or cyclone

Theoretical Models

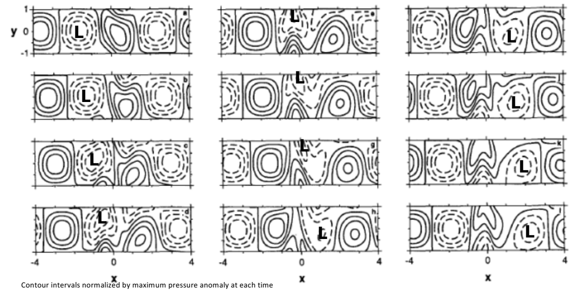
- View lee cyclogenesis as the result of the interaction of a synoptic-scale trough or cyclone with a mountain ridge (e.g., Tibaldi et al. 1990; Bannon 1992)
- Observed cyclone evolution results from superposition of
  - A growing baroclinic wave (a.k.a., the primary baroclinic wave)
  - Secondary topographic eddies produced by the interaction of the primary baroclinic wave with the topography
- The primary baroclinic wave would exist and grow even in the absence of topography
- Secondary eddies alter the structure, growth, and track of the primary baroclinic wave

Conceptual model



Bannon (1992)

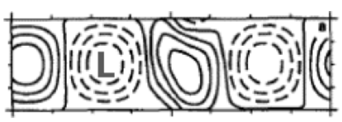
QG Cyclone Evolution

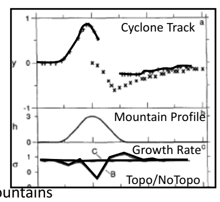


Superposition of primary cyclone and topographic eddies results in "amoeba-like" movement of cyclone across a mountain ridge

Bannon (1992)

QG Cyclone Evolution

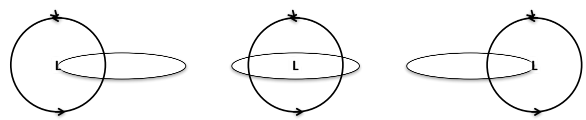




- Low deflected to northeast as it approaches mountains
- Growth rate slows and becomes negative (mountain is cyclolytic)
- Lee trough develops as cyclone impinges on mountain
- Low appears to lee of mountains, equatorward of its original latitude, and is not traceable upstream (discontinuous progression)
- Enhanced growth rate to the lee
- Low briefly moves southeast before moving northeast

Bannon (1992)

Class Discussion



What happens as a primary cyclone traverses an isolated, "Alps-like" zonally oriented barrier?

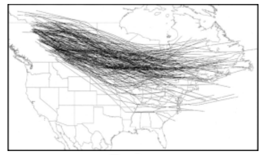
Note: Barrier is highest in the middle

Mechanisms Summary

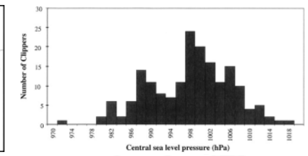
- Orographic cyclone evolution can be viewed as the superposition of a parent cyclone and topographic pressure perturbations generated by its interaction with orography
- This superposition results in the "amoeba-like" movement of cyclones across the Rockies
- For an isolated barrier like the Alps, growth rate is less strongly influenced, but cyclone structure is distorted
- Advantage: the conceptualization can be generalized to a number of different flow conditions and mountain geometries
- Caveats
  - Actual growth rates are much stronger than simulated by QG (Eady-type) models
  - Theory does not fully account for steep orography, diabatic effects, nonlinearities, etc.

Alberta Cyclones

Synoptic Characteristics



Tracks

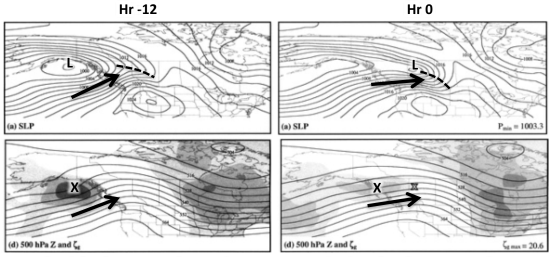


Lowest Central MSLP

The central MSLP is ≤ 990 mb only 7% of the time
Only 28% reach ≤ 992 mb [arbitrary "strong cyclone" threshold (Angel and Isard 1997)]

Thomas and Martin (2007)

Composite

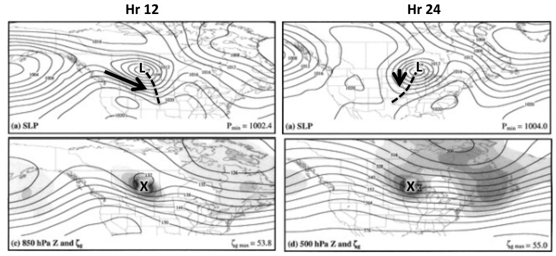


Frontal cyclone approaches coast
Stationary lee trough develops due to
to cross barrier flow & vortex stretching

Lee trough and warm anomaly
amplify & broaden
Cyclogenesis as CVA moves into lee

Palmén and Newton (1969), Thomas and Martin (2007), Steenburgh and Mass (1994)

Composite

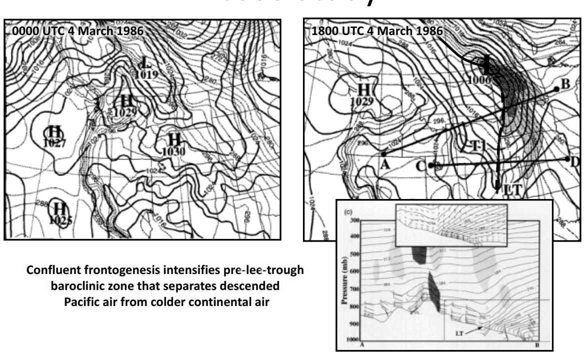


Cessation of downslope flow
Ongoing deepening due to synoptic forcing
Lee trough broadens in scale as
air warmed by descent spreads eastward

Northern portion of lee trough
moves eastward
Southern portion remains fixed to Rockies

Palmén and Newton (1969), Thomas and Martin (2007), Steenburgh and Mass (1994)

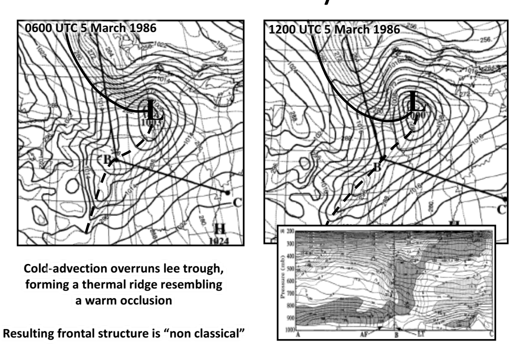
Case Study



Confluent frontogenesis intensifies pre-lee-trough
baroclinic zone that separates descended
Pacific air from colder continental air

Steenburgh and Mass (1994)

Case Study



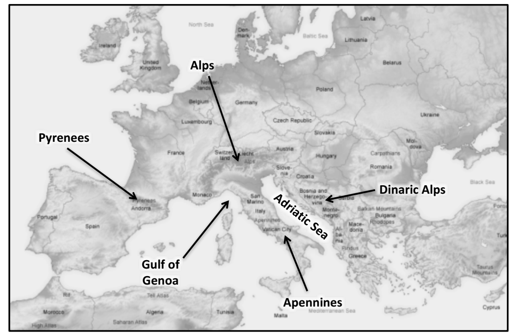
Cold-advection overruns lee trough,
forming a thermal ridge resembling
a warm occlusion

Resulting frontal structure is "non classical"

Steenburgh and Mass (1994)

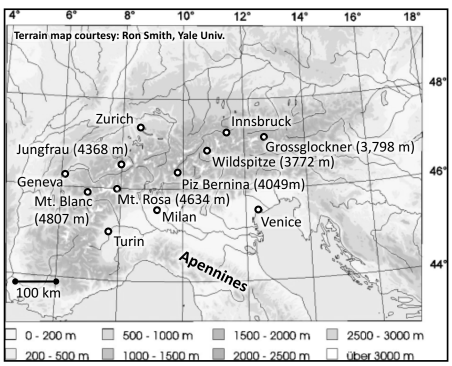
Alpine Lee Cyclogenesis

European geography

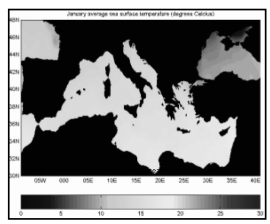


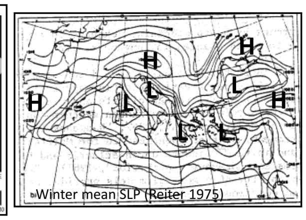
Map: Wikipedia Commons

European Geography



Climatology of the Mediteranean

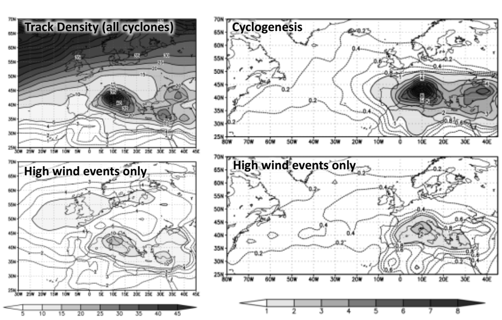




- During winter (Jan), Mediterranean SSTs range from 12-20ºC, roughly 2-4ºC warmer than the mean air temperature
- Mediterranean represents a time-averaged heat source during the cool season, with the surrounding region experiencing a temperate climate
- Mean low pressure over the Mediterranean with an estimated amplitude of 5 mb

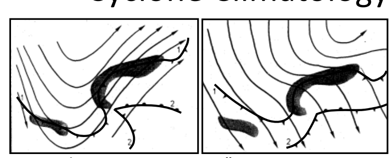
Naval European Meteorology and Oceanography Center, Reiter (1975), Buzzi and Speranza (1983)

Cyclone Climatology



Nissen et al. (2010), ERA-40 (1.25ºx1.25º) MSLP Cyclones Oct–Mar 1957–2002

Cyclone Climatology



Vorderseiten type   *Überströmungs* type

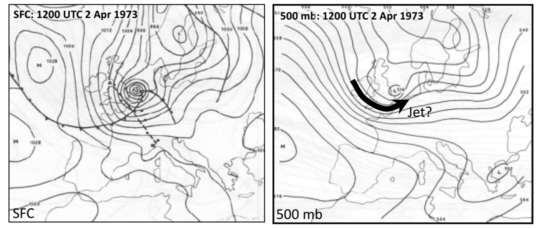
Pichler and Steinacker (1987)

- Most are “Alpine Lee Cyclones” are shallow thermal and/or orographic lows;
  - Buzzi and Speranza (1983) claim only 5-6/year develop into deep cyclones
  - Tibaldi et al. (1990) claim 10-20 moderate to strong events a year
  - Explosive deepening (e.g., Sanders and Gyakum 1980) is rare (Tibaldi et al. 1990)
- Pichler and Steinacker (1987) describe two types of Alpine lee cyclones
  - *Vorderseiten* type, associated with southwesterly upper-level flow
  - *Überströmungs* type, associated with northwesterly upper-level flow
- Both types associated with blocking and distortion of low-level cold front

General Characteristics

- Most events are not purely orographic
- Cyclogenesis occurs occurs when:
  - An upper-level trough is upstream of the Alps
  - A low-level frontal system impinges on the Alps
  - An upper-level "forcing" (e.g., CVA, coherent tropopause disturbance, left exit region, etc.) moves over the northern Mediterranean
- Alpine lee cyclones are typically smaller in scale than traditional midlatitude cyclones
- Can be accompanied by the Mistral (France), Foehn (Austria), or Bora (Italy, Slovenia, Croatia), and can be followed by a Mediterranean cold-air outbreak

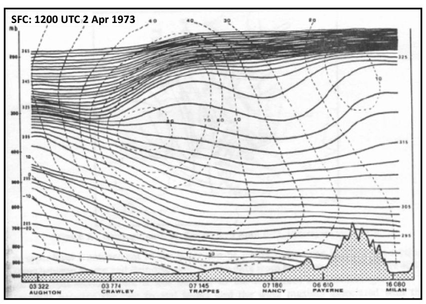
Classic View: Antecedent Stage



- Cyclone & upper-level trough/jet streak into central Europe
- The accompanying cold front approaches the Alps
- Cyclogenesis is inhibited beneath the upper-level trough by cold advection (weak QG vertical motion at mid levels)

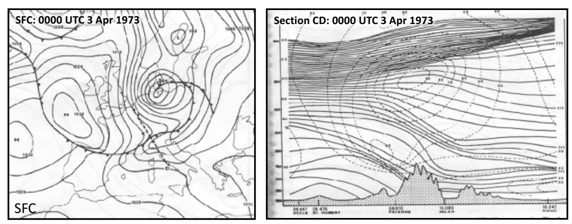
Buzzi and Tibaldi (1978)

Classic View: Antecedent Stage



Buzzi and Tibaldi (1978)

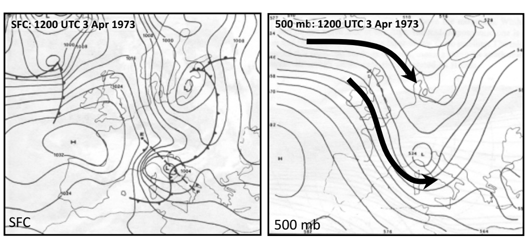
Classic View: Trigger Stage



- Cold front is blocked and distorted by Alps, resulting in frontogenesis and steepening of the frontal slope
- Positive thermal anomaly forms in lee at low levels (adiabatic warming)
- Initial depression appears in lee of Alps ahead of, not on, the cold front

Buzzi and Tibaldi (1978)

Classic View: Trigger Stage



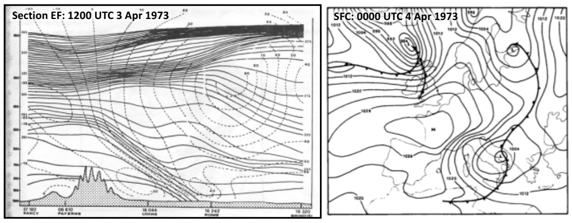
- Cyclone deepens while remaining quasistationary
- Upper-level trough fills north of alps, but deepens to the south
- Jet splits northwest of Alps

Buzzi and Tibaldi (1978)

Classic View: Trigger Stage

- Proposed mechanisms for cyclogenesis
  - Secondary circulation (mid-level ascent) associated with cold front (Buzzi and Tibaldi 1978; McGinley 1982)
  - Terrain induced low-level subsidence (Buzzi and Tibaldi 1978; McGinley 1982)
  - Mid-level ascent associated with increasing CVA with height downstream of trough (Bluestein 1993)
  - Mid-level ascent found in left-exit region of jet (Mattocks and Bleck 1986)
  - PV thinking with Alpine PV banner (McTaggert-Cowan et al. 2010a,b)
- Latent heat release not always important
  - Extensive cloud and precipitation are not usually observed during this period, but can become important later (Tibaldi et al. 1990)
  - However, McTaggert-Cowen et al. (2010a,b) describe an event in which latent heating in the orographic cloud contributes to the leeward warm anomaly and subsequent diabatic heating over the Gulf of Genoa contributes to the formation of a "Mediterranean Hurricane"

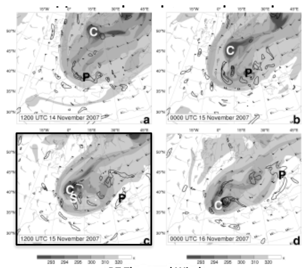
Classic View: Baroclinic Stage



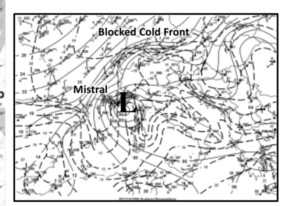
- Front and vertical circulation "reunite" and become structurally continuous (note: no cross section available for 0000 UTC 4 Apr)
- More traditional baroclinic development occurs
- Cyclone moves away from Alps with a character similar to a traditional frontal cyclone

Buzzi and Tibaldi (1978)

PV View

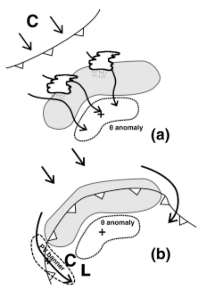


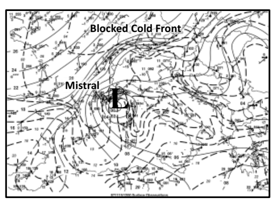
DT Theta and Wind
925–850-mb mean relative vorticity



McTaggert-Cowan et al. (2010a,b)

PV View



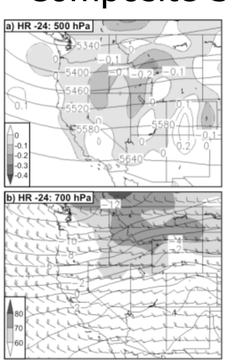


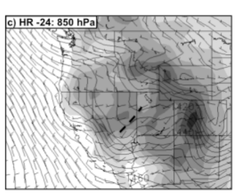
Leeward theta anomaly generated by cold-frontal retardation, heavy precipitation and diabatic heating on windward side of Alps, and adiabatic descent
Eventually PV banner provides an additional contribution

McTaggert-Cowan et al. (2010a,b)

Intermountain Cyclones

Composite SW Flow Event

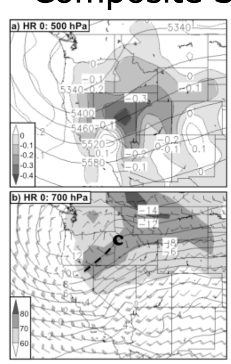


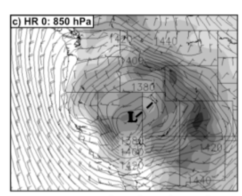


Intermountain cyclogenesis is preceded by the development of the GBCZ downstream of High Sierra

Jeglum et al (2010)

Composite SW Flow Event

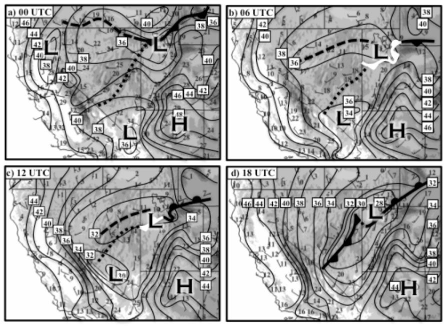




GBCZ serves as locus for cyclogenesis as ascent associated with upper-level trough moves into lee of Sierra

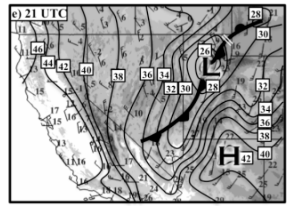
Jeglum et al (2010)

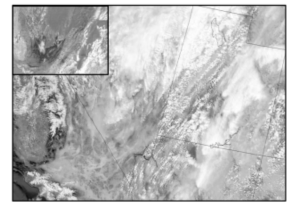
Tax Day Storm



West and Steenburgh (2010)

Tax Day Storm





West and Steenburgh (2010)

Tax Day Storm

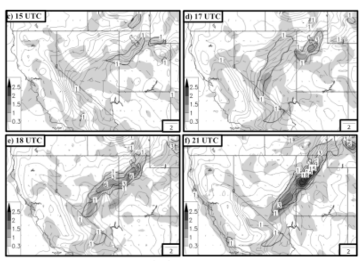
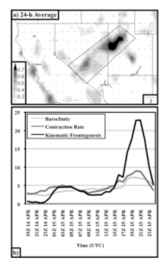


Figure 11. ADAS contraction ($x10^{-4}$ s^{-1}, shaded according to inset scale), kinematic frontogenesis (black contours every 3 K $(100\ km)^{-1}$ h^{-1}), local orientation of axes of dilatation scaled by magnitude of contraction ($x10^{-4}$ s^{-1}, according to inset scale), and potential temperature (gray contours every 2 K) at (a) 0000 UTC, (b) 1200 UTC, (c) 1500 UTC, (d) 1700 UTC, (e) 1800 UTC, and (f) 2100 UTC 15 Apr.

West and Steenburgh (2010)

Tax Day Storm



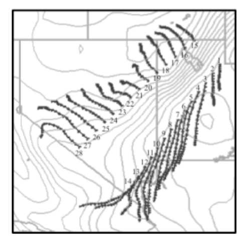


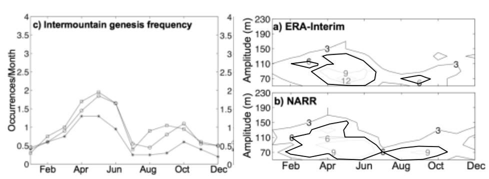
Figure 12. (a) Temporally-averaged contraction ($x10^{-4}$ s^{-1}, shaded according to inset scale,) and local orientation of axes of dilatation scaled by magnitude of contraction ($x10^{-4}$ s^{-1}, according to inset scale) from 2100 UTC 14 Apr – 2100 UTC 15 Apr. (b) Areally-averaged contraction ($x10^{-4}$ s^{-1}), baroclinity (K $(100\ km)^{-1}$), and kinematic frontogenesis ($x10^{-1}$ K $(100\ km)^{-1}$ h^{-1}) within the quadrilateral denoted in (a).

West and Steenburgh (2010)

Summary

- Mountains have a profound effect on the genesis, lysis, track, and evolution of cyclones
- Geographic variations in the structure and evolution of orographic cyclones arise from unique regional climate and topographic characteristics
- It can be helpful to view orographic cyclone evolution as the superposition of a parent cyclone and topographic pressure perturbations generated by its interaction with orography
- PV thinking may be applicable to a wider range of events given the broad spectrum of large-scale environments in which orographic cyclogenesis occurs, but has only been utilized by a few authors (e.g. McTaggert-Cowen et al. 2010a,b)

Class Discussion



- Why are Intermountain cyclones deeper and more frequent in the spring?
- What dynamical processes might contribute to the development of the GBCZ?
- The Sierra matter, but how might other terrain features in and surrounding the Great Basin contribute to Intermountain cyclone development and evolution?
- How could we use PV thinking to better understand Intermountain cyclogenesis?

Jeglum et al. (2010)

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