Orographic Precipitation I:

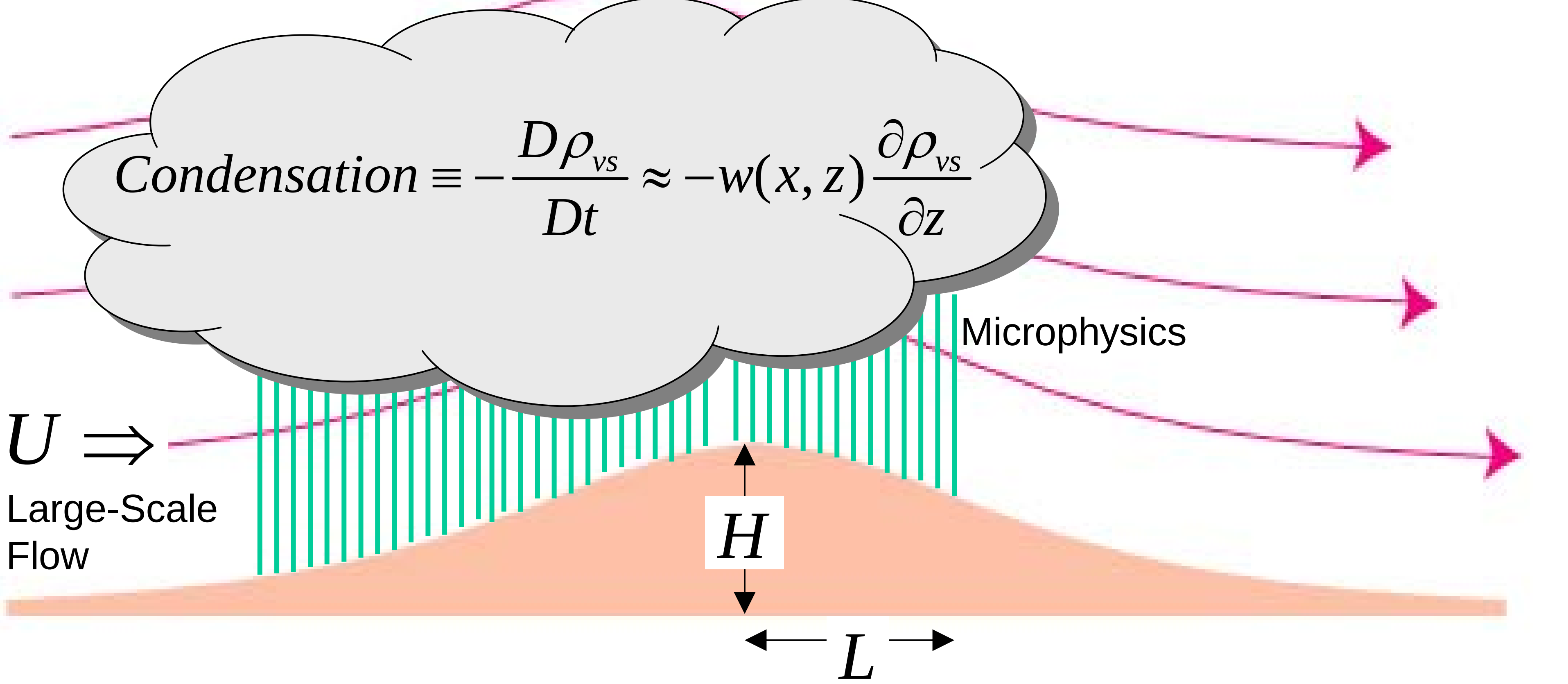
Observation and Theory Overview

Richard Rotunno

National Center for Atmospheric Research , USA

"To explain the amount and distribution of orographic rain …requires consideration of aspects of meteorology on three different scales. First, there are the large-scale synoptic factors which determine the characteristics of the air mass which crosses the hills, its wind speed and direction, its stability and humidity. Second there is the dynamics of the air motion over and around the hill or hills with which we are concerned; this determines to what depth and through what layer of the air mass is lifted. Thirdly, there is the microphysics of the cloud and rain, which determines whether the water which is condensed as cloud will reach the ground as rain or snow, or whether it will be merely re-evaporated on the leeward side."

J. S. Sawyer (1956)

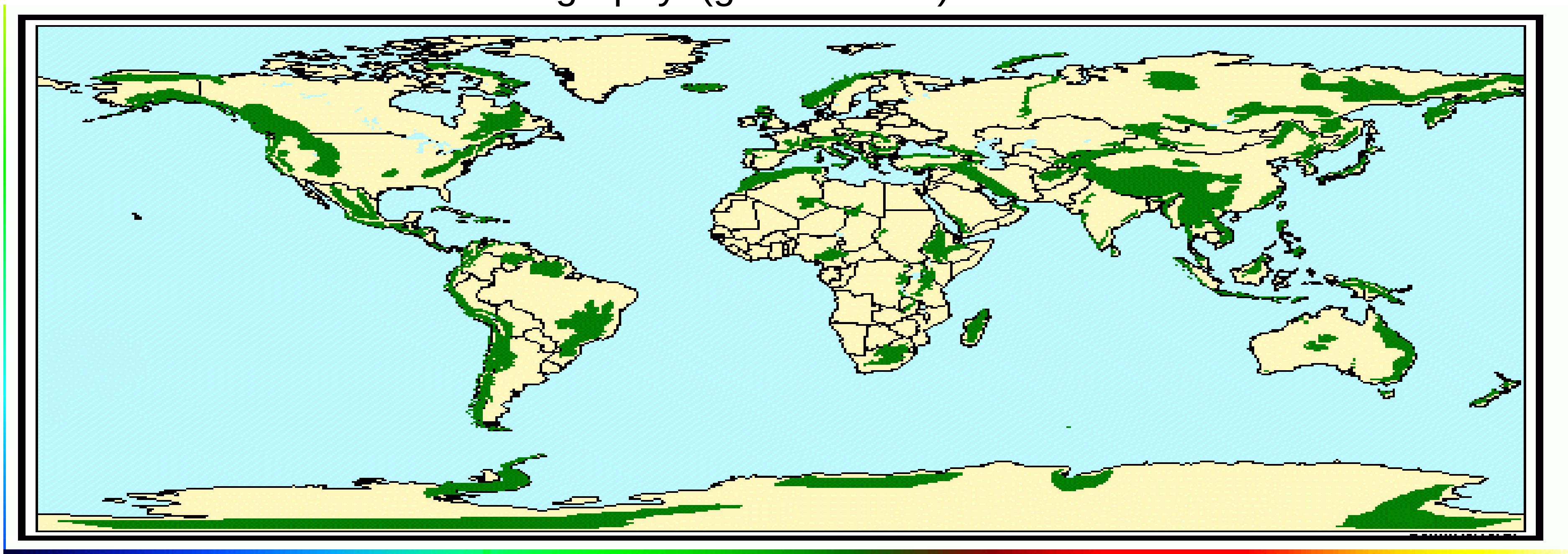


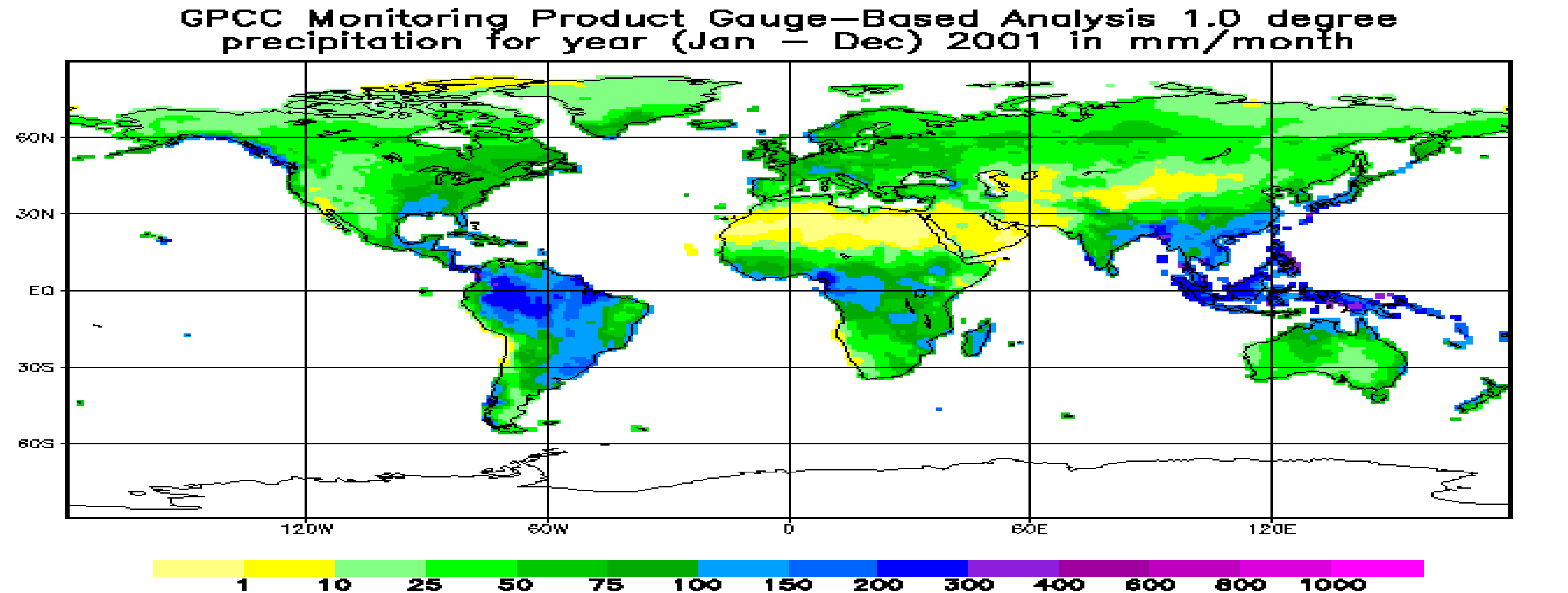
$$w = w(H, L, U, Stability, Coriolis, 3D\ Effects)$$

w	=	vertical velocity
ρ_{vs}	=	saturation vapor density

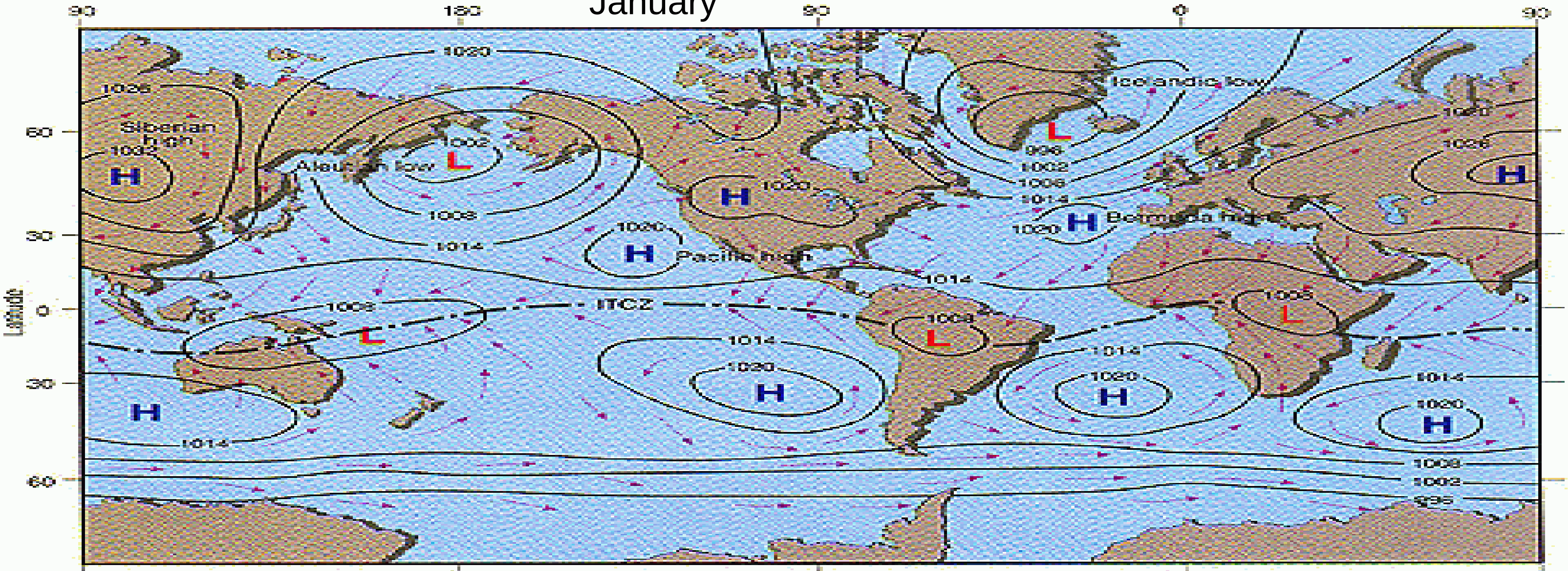
…large-scale synoptic factors…

Orography (green > 1km)

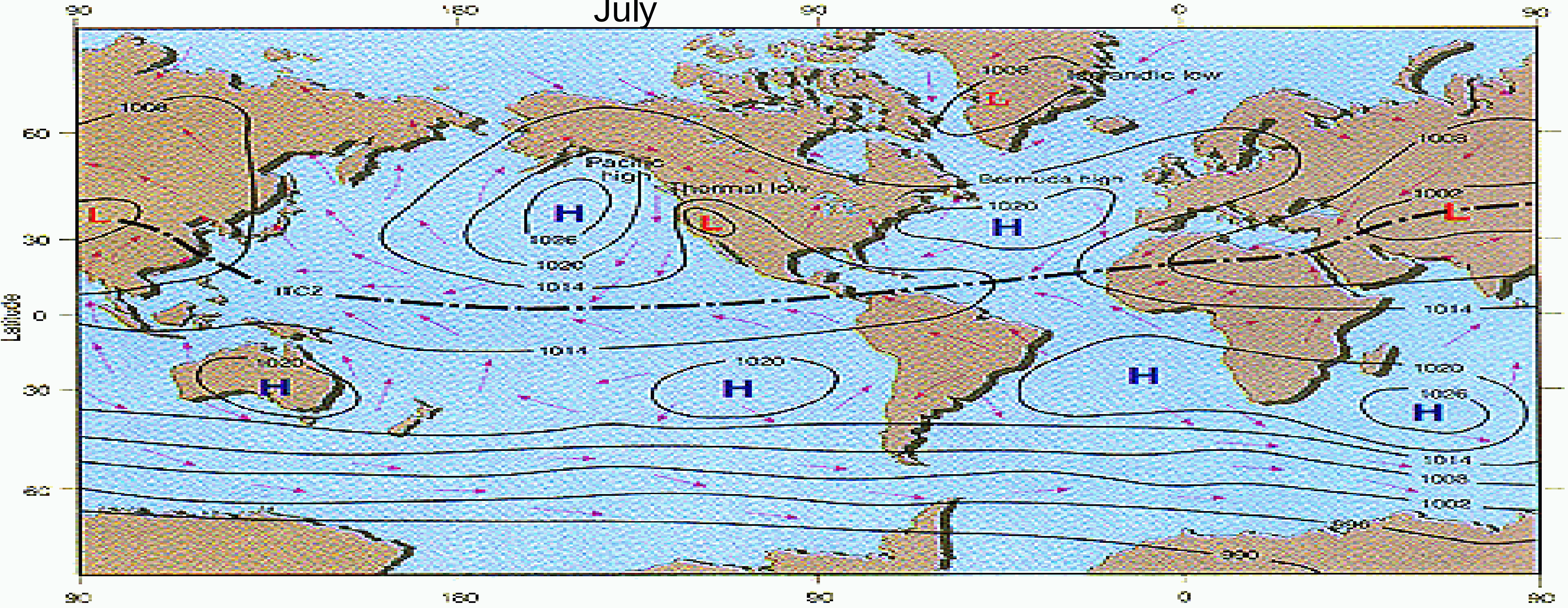




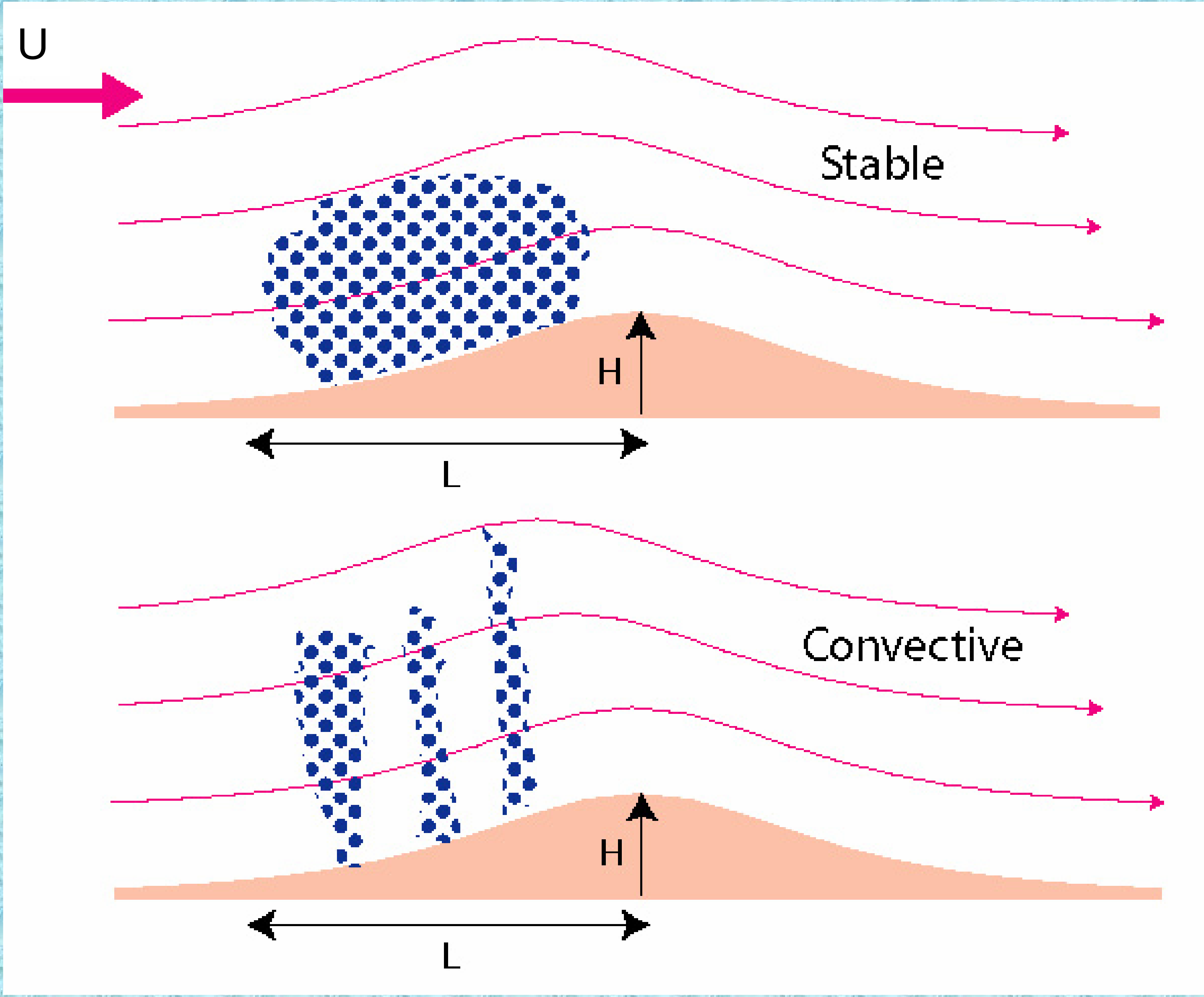
January



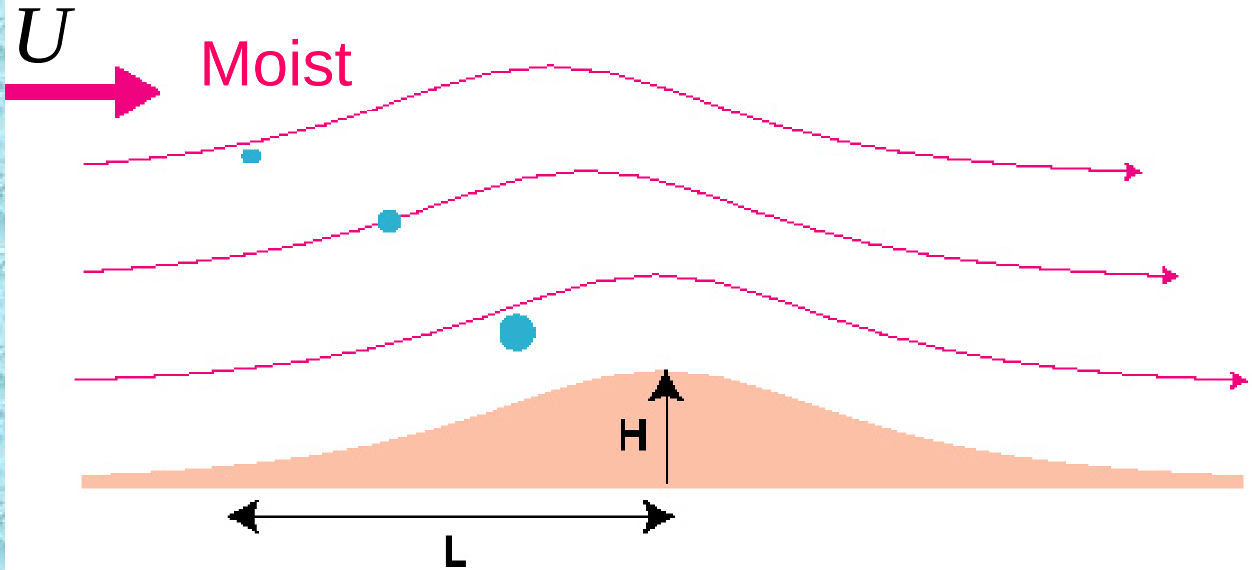
July



…dynamics of the air motion over and around the hill…


U
Stable
H
L
Convective
H
L

…microphysics of the cloud and rain…



$$\tau_{microphysics} \ll \tau_{airflow}$$

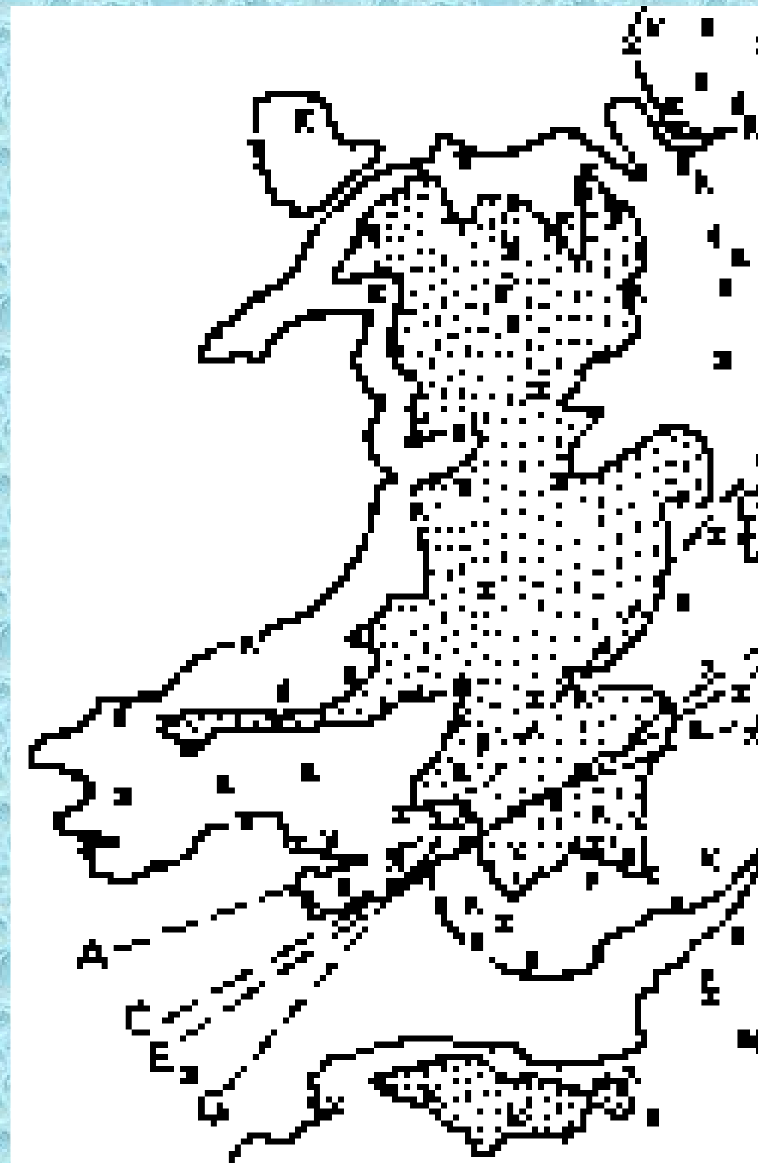
$$1000s \ll \frac{L}{U}$$

$$U = 10m/s$$

L	L/U
$100km$	$10000s$
$10km$	$1000s$

A Few Examples

Wales , UK (stippled > 150 m)



100 km

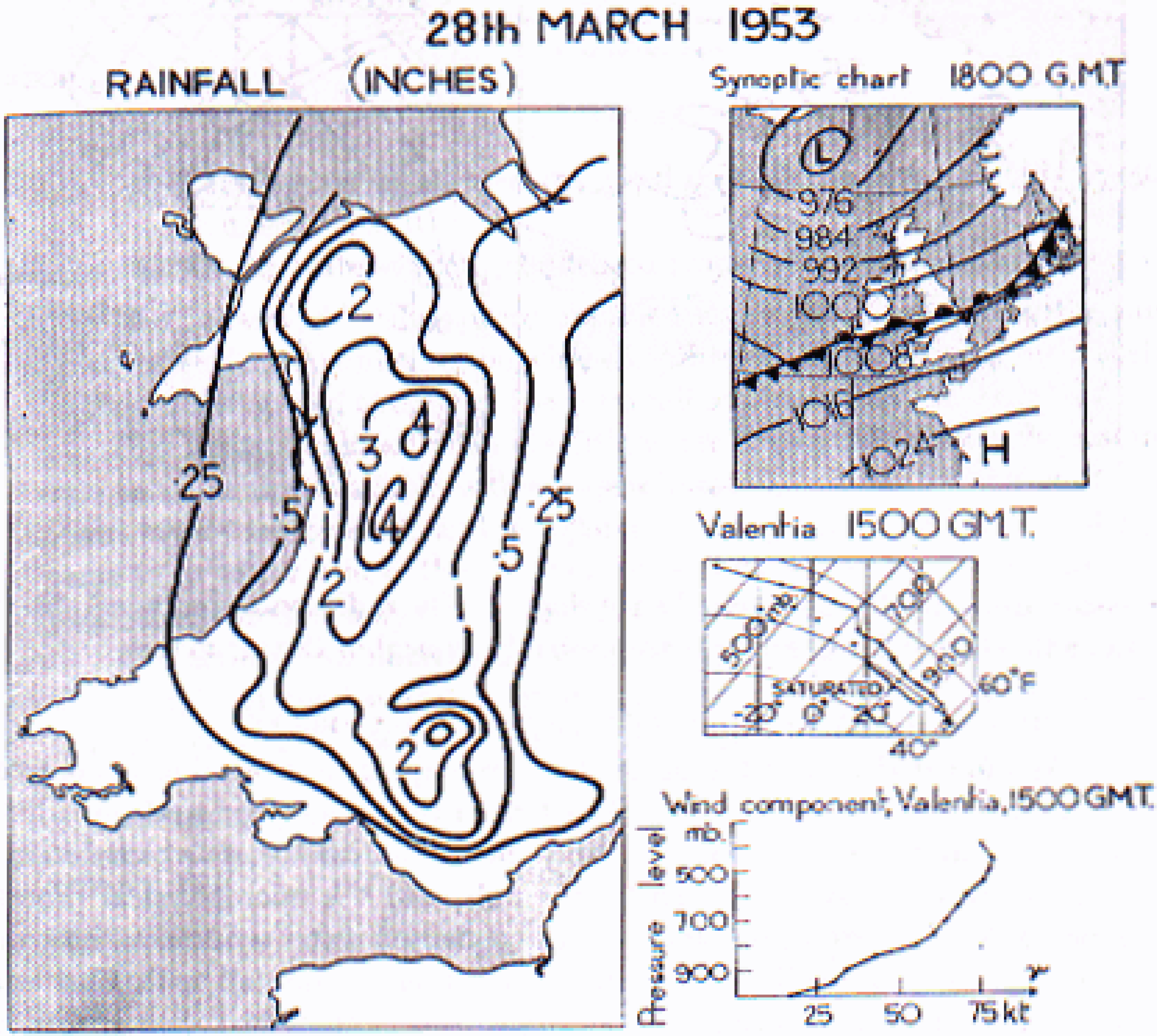


Fig. 2

Sawyer (1956)

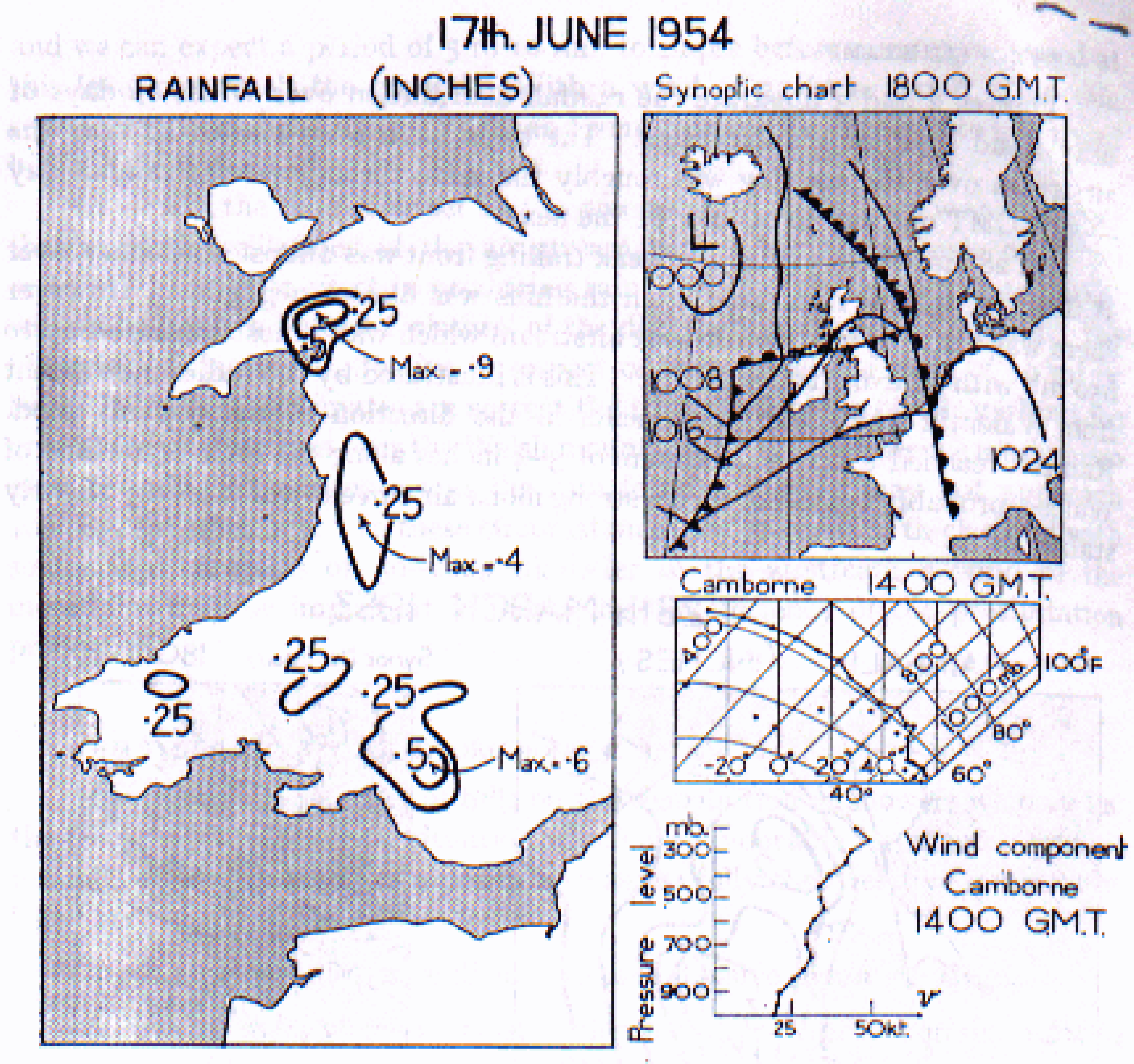
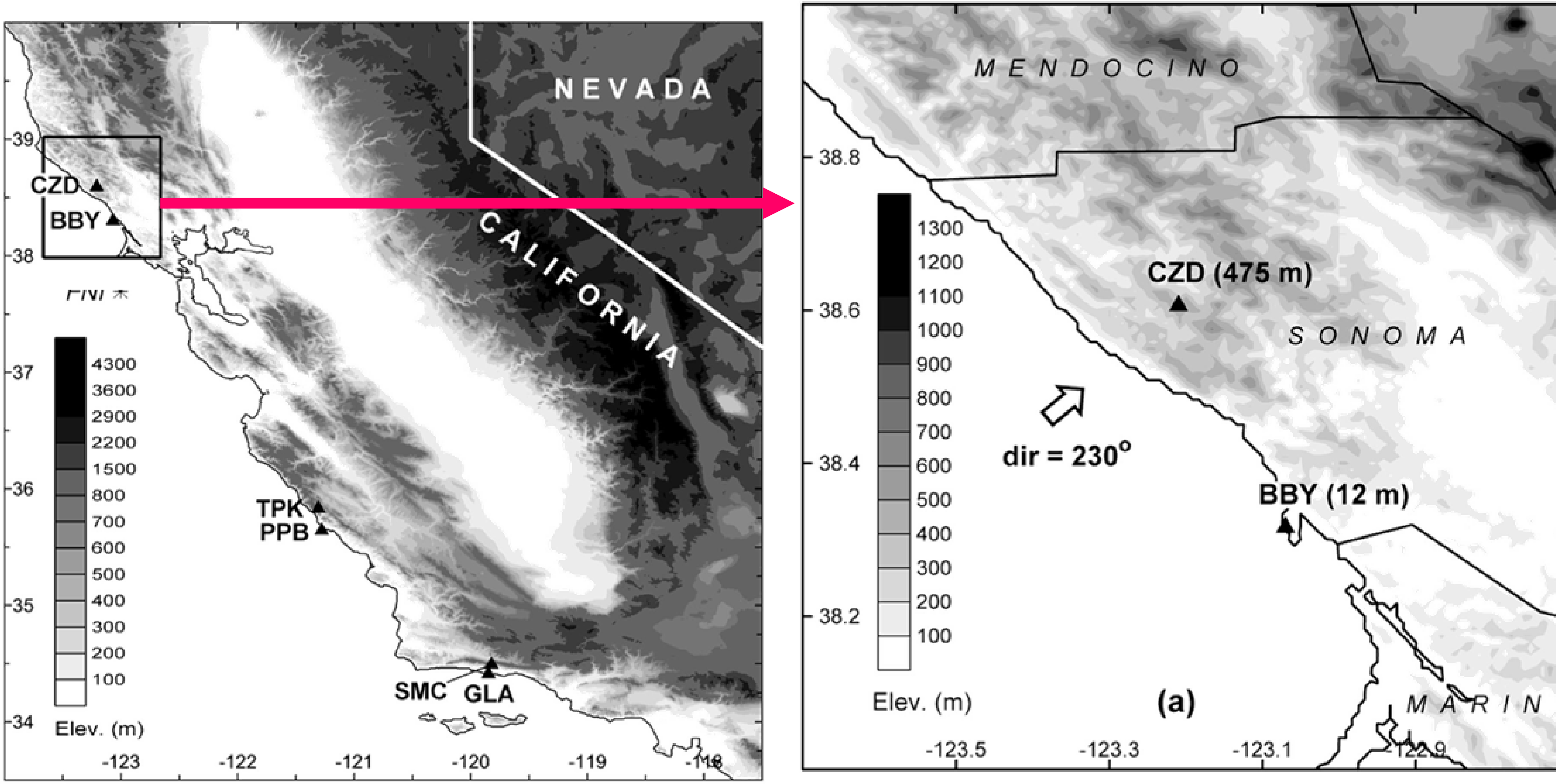


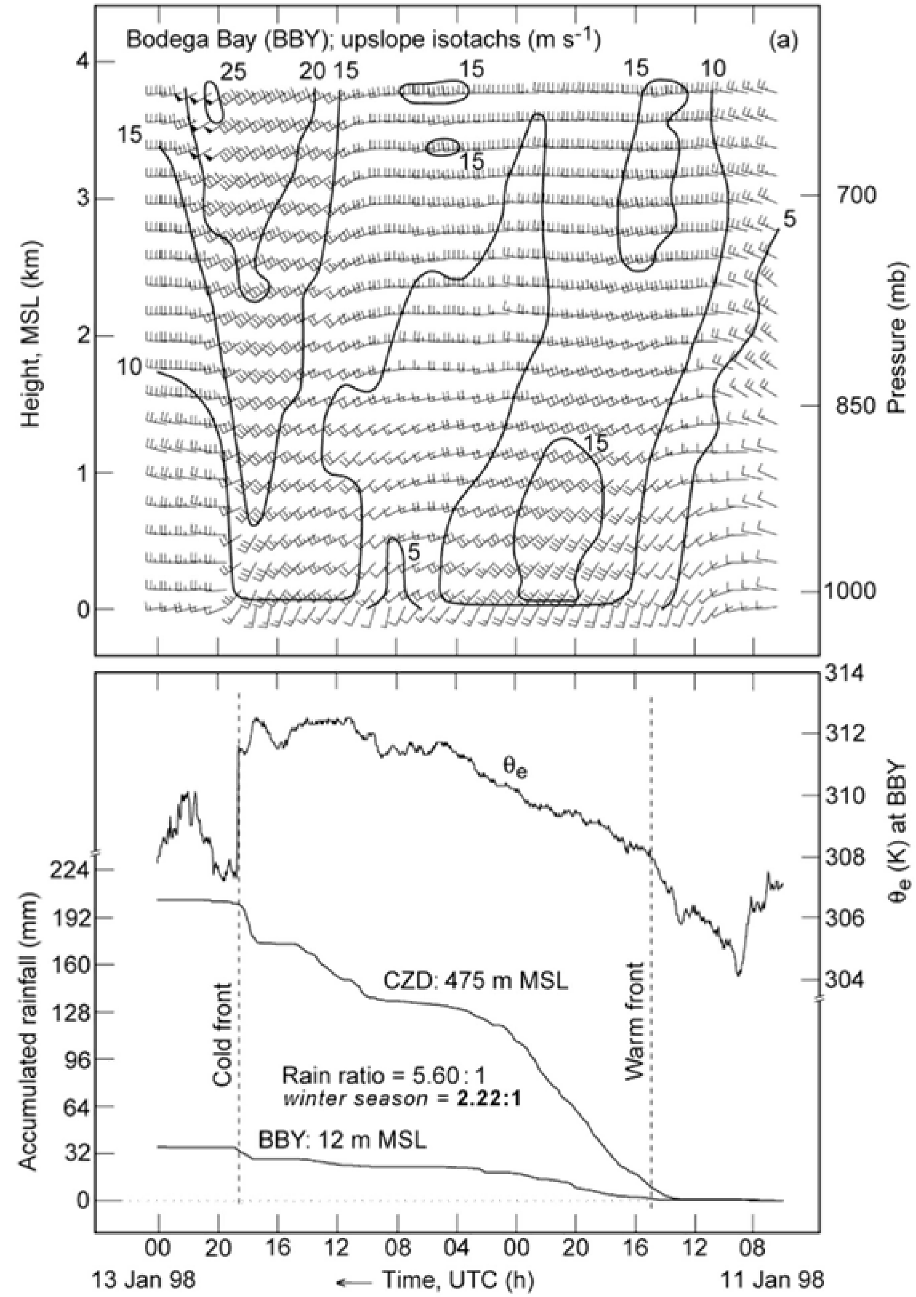
Fig. 3

Sawyer (1956)



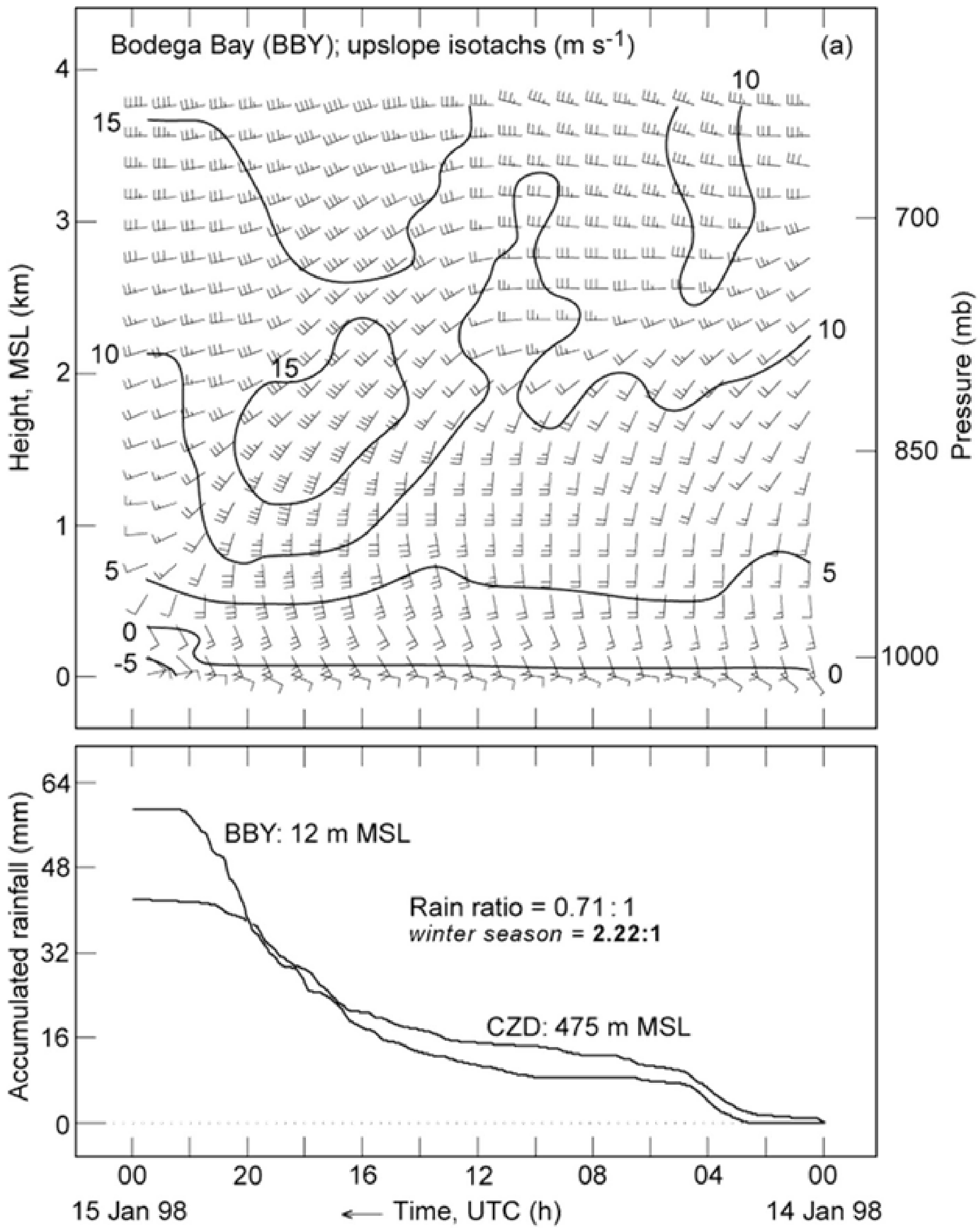
Neiman et al. (2002)

Unblocked

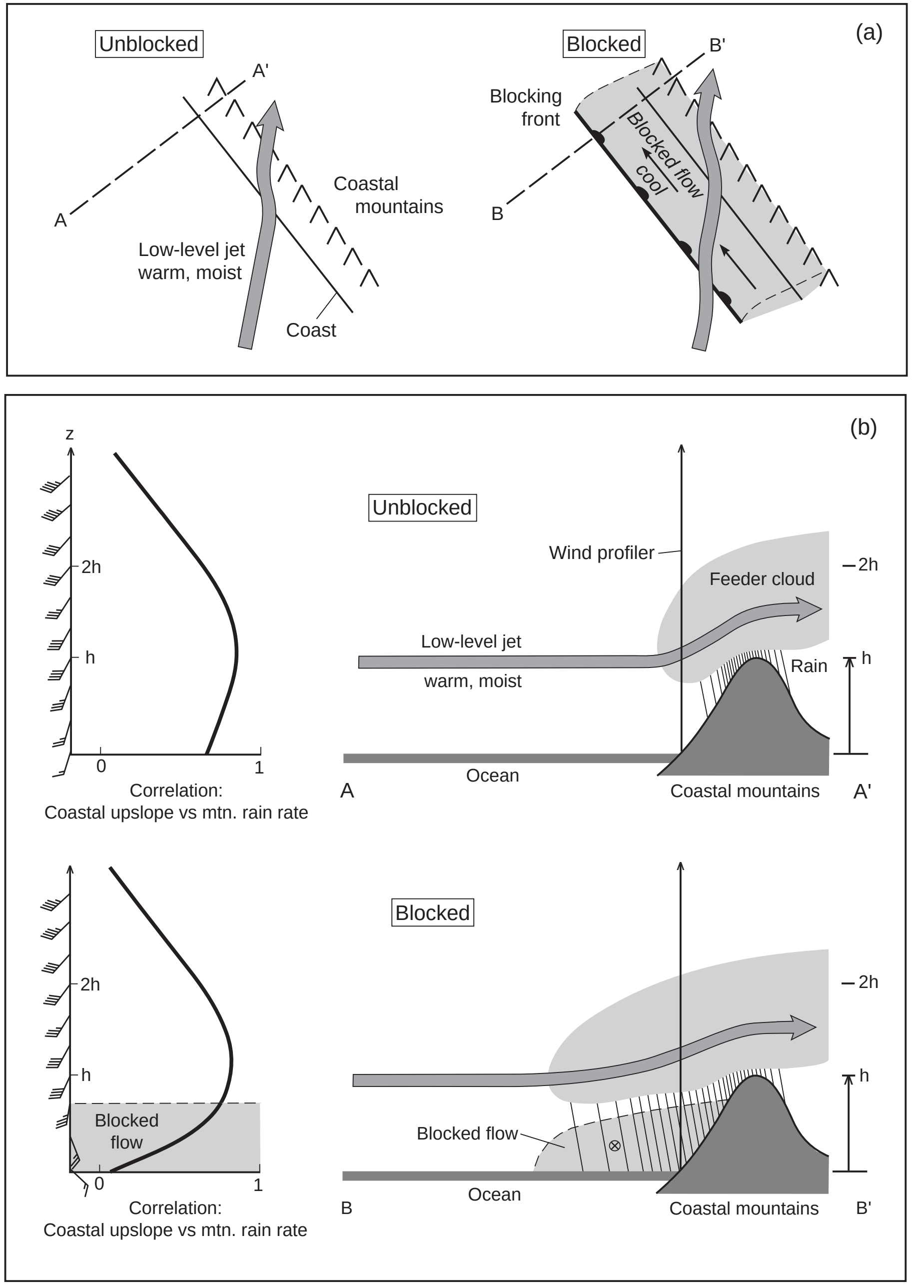


Bodega Bay (BBY); upslope isotachs (m s-1)
(a)
Height, MSL (km)
Pressure (mb)
700
850
1000
Accumulated rainfall (mm)
θe (K) at BBY
θe
CZD: 475 m MSL
BBY: 12 m MSL
Cold front
Warm front
Rain ratio = 5.60 : 1
winter season = 2.22:1
13 Jan 98
← Time, UTC (h)
11 Jan 98

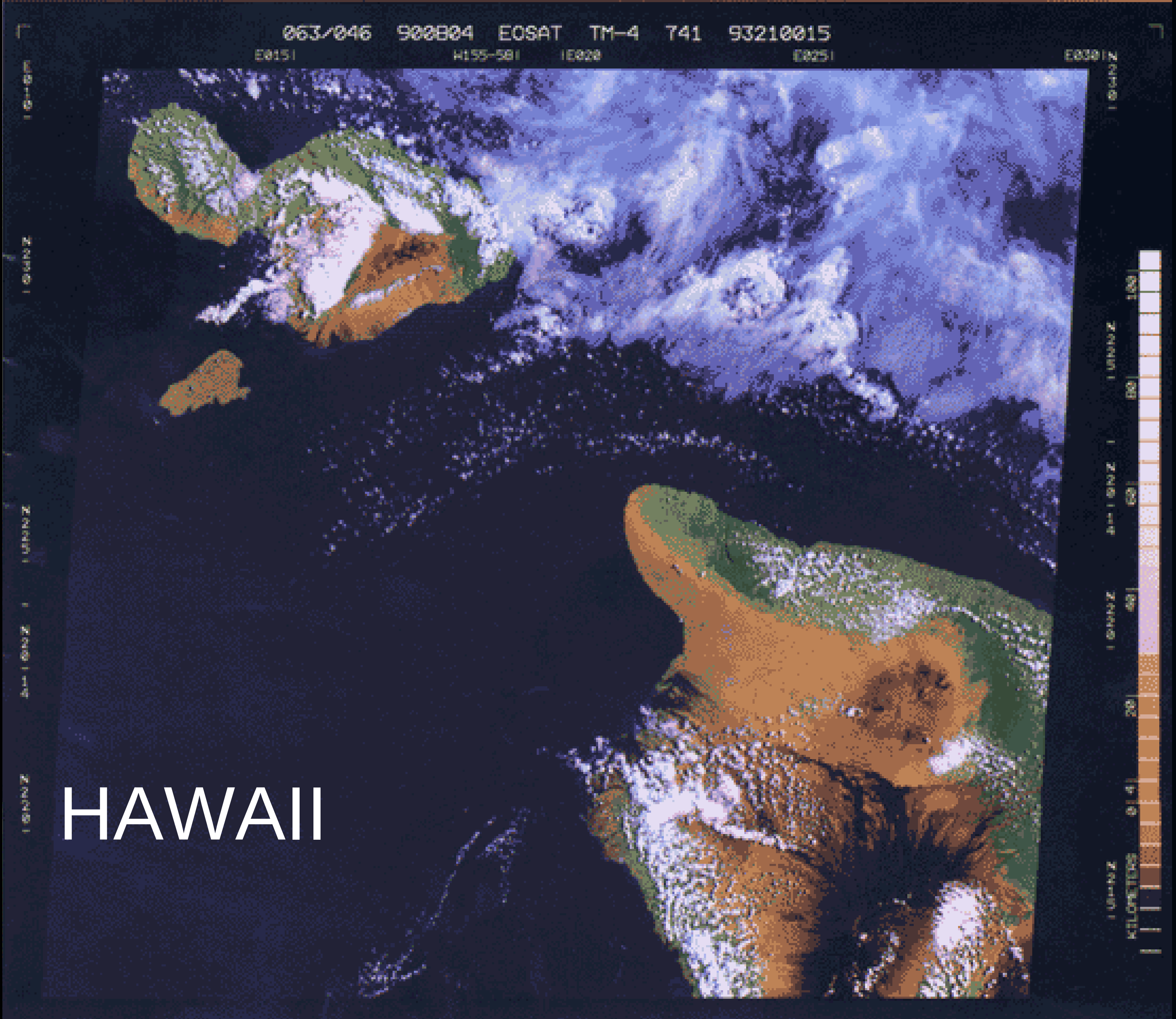
Blocked

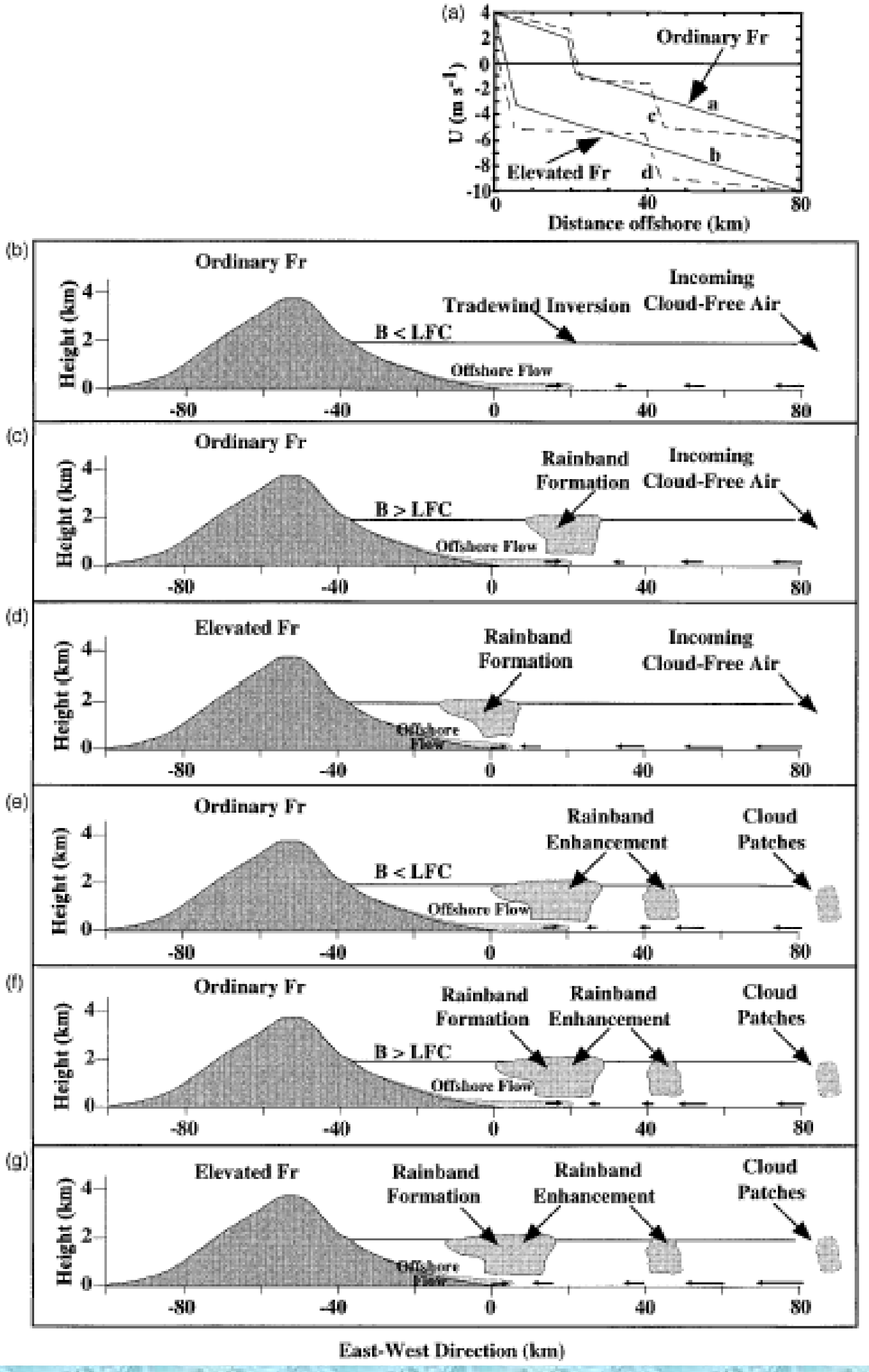


Bodega Bay (BBY); upslope isotachs (m s-1)
(a)
Height, MSL (km)
Pressure (mb)
700
850
1000
15
10
5
0
-5
BBY: 12 m MSL
Rain ratio = 0.71 : 1
winter season = 2.22:1
CZD: 475 m MSL
Accumulated rainfall (mm)
00
20
16
12
08
04
15 Jan 98
← Time, UTC (h)
14 Jan 98



- Rain rate in coastal mtns directly linked to upslope flow at coast.
- In blocked flow, near-sfc winds do not provide useful rain-rate info.


063/046 900804 EOSAT TM-4 741 93210015
HAWAII



HAWAII

$$B = \frac{U}{N}$$

$$Fr = \frac{U}{NH}$$

Wang, Rauber, Ochs
And Carbone (2000)

Oahu Flood, Hawaii 1974

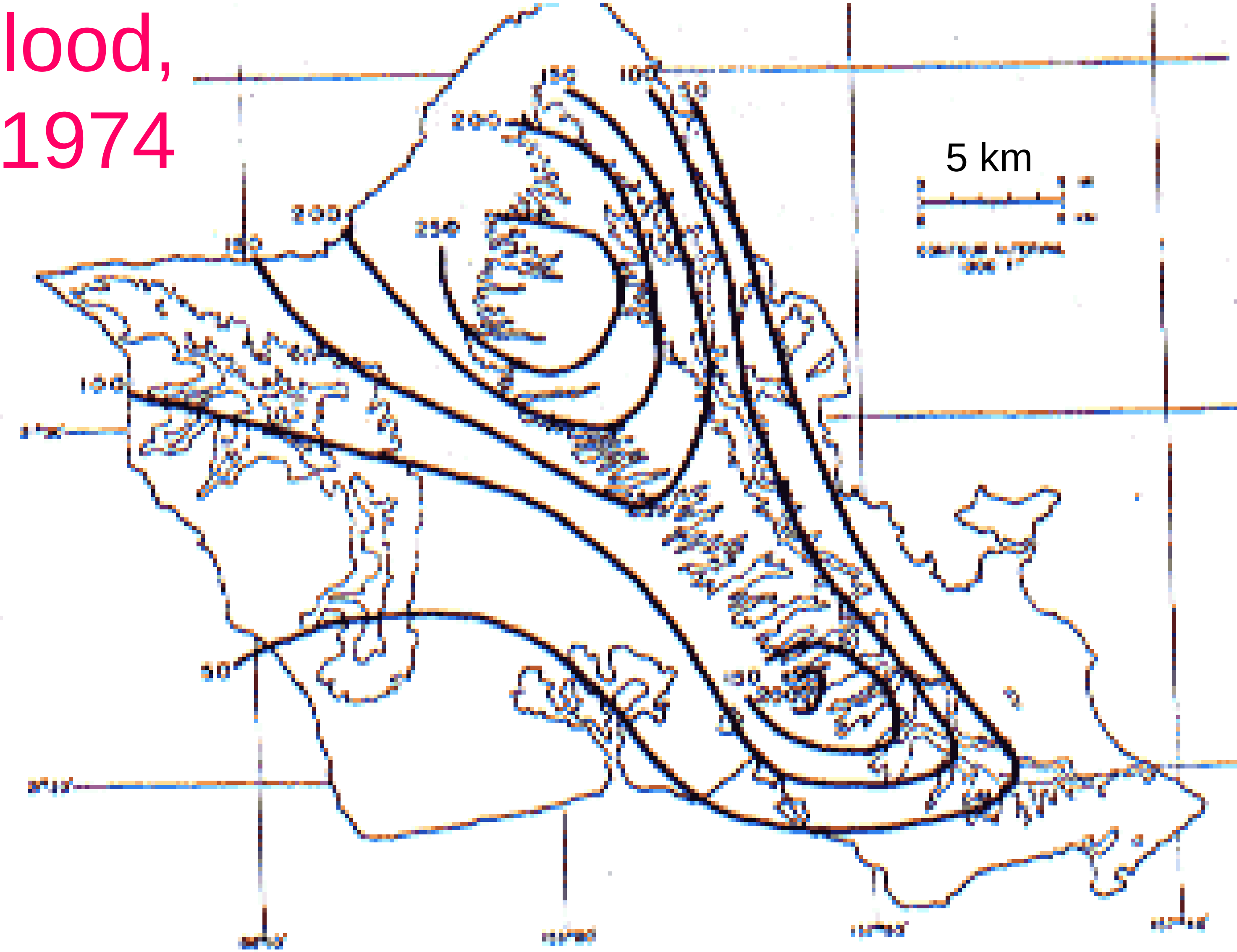
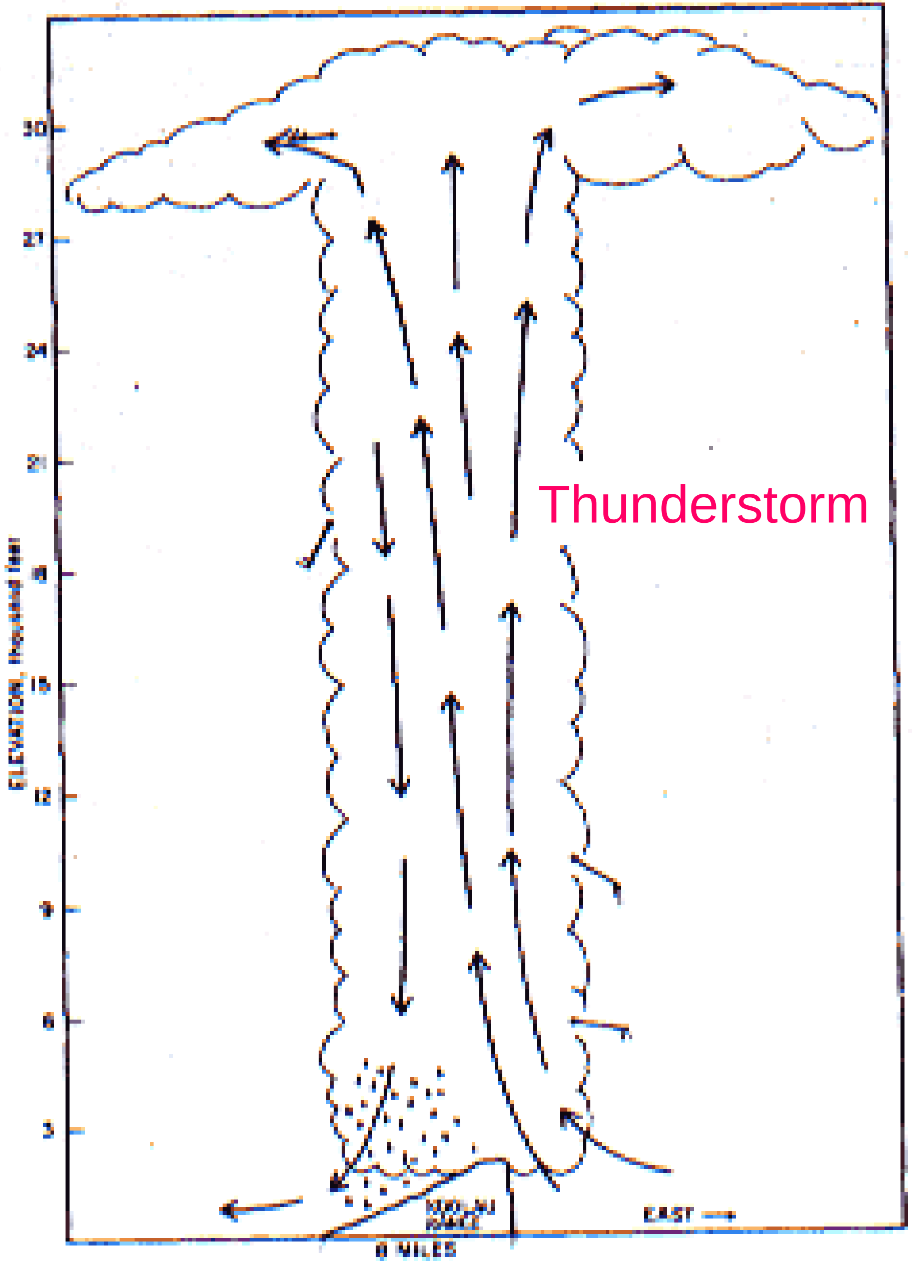


FIG. 7. Analyzed storm isohyets for period 0200 to 1500 hours on 19 April 1974. Isohyets are in millimeters.

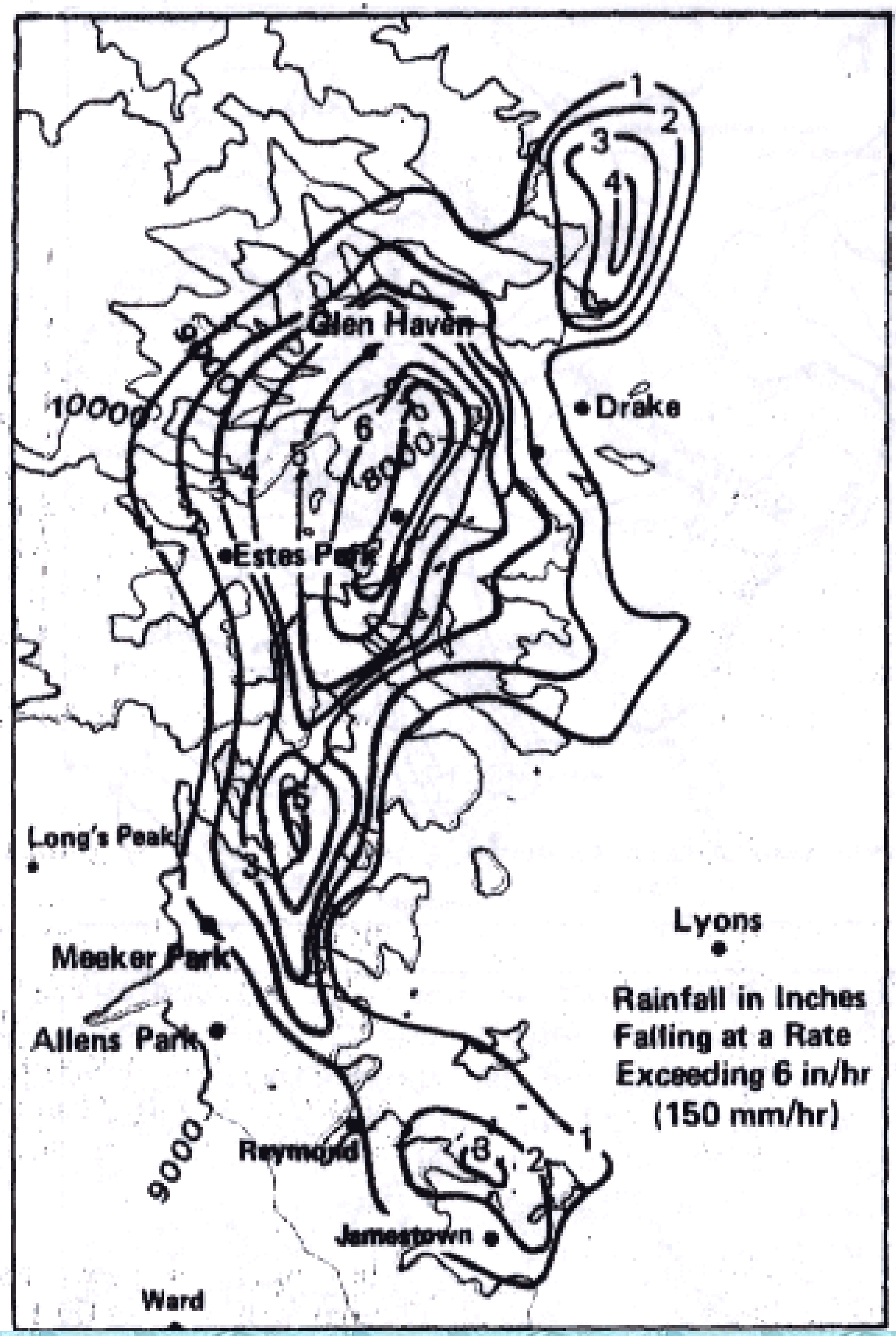
$$R_{\max} \approx 70\, mm / h$$

Schroeder (1977)

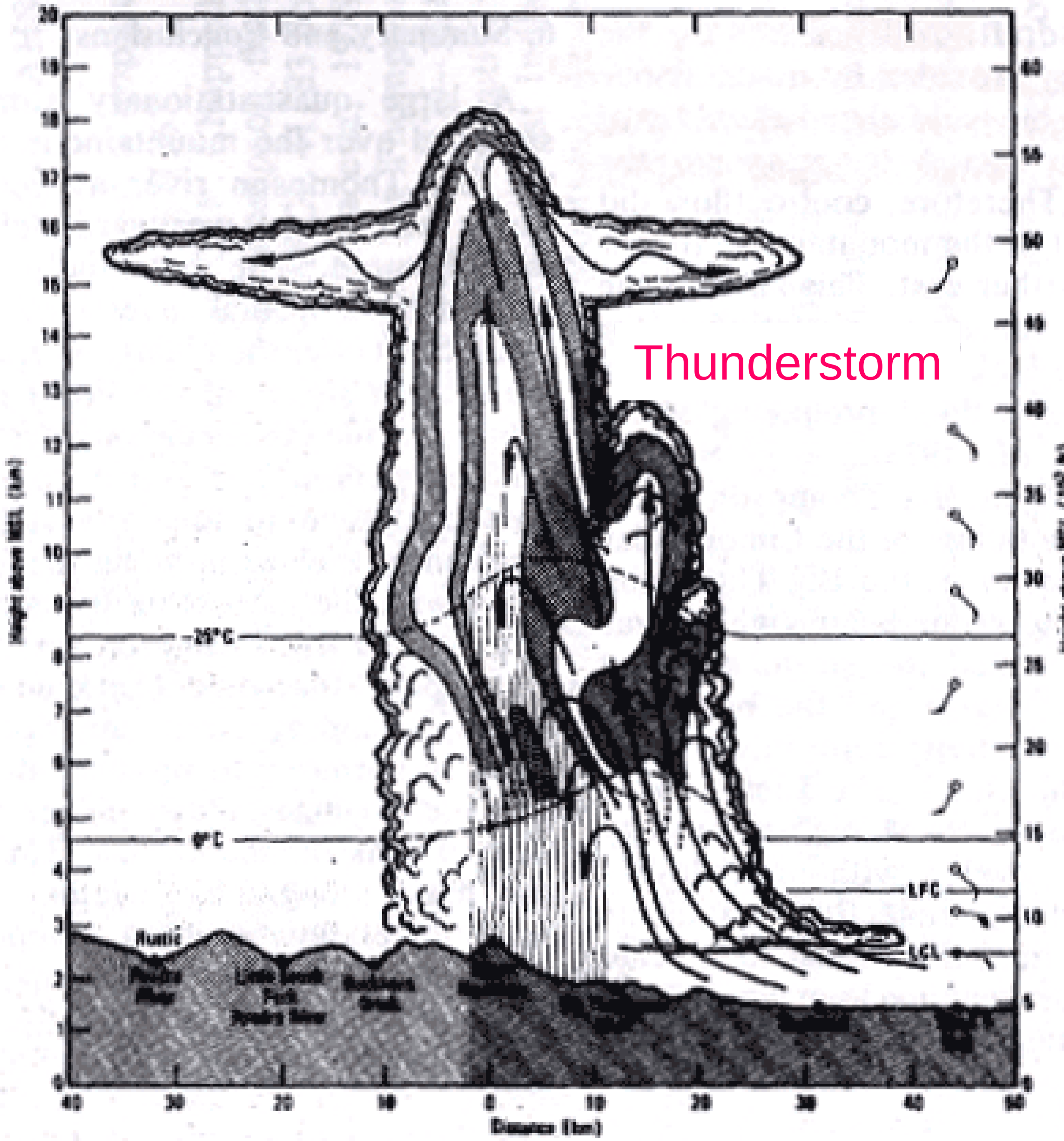


Schroeder (1977)

Big Thompson Flood Colorado, 1976

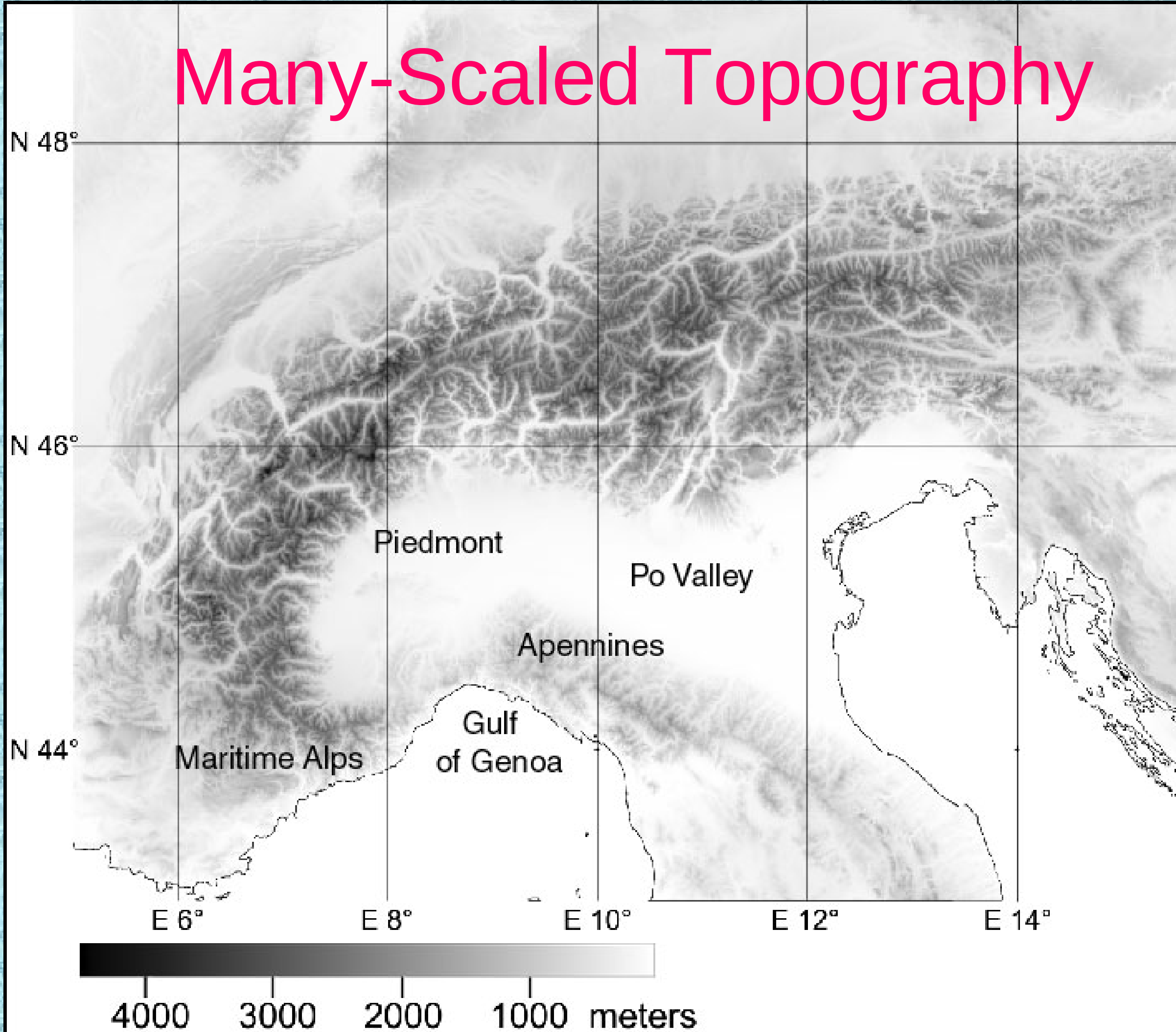


Caracena et al. (1979)

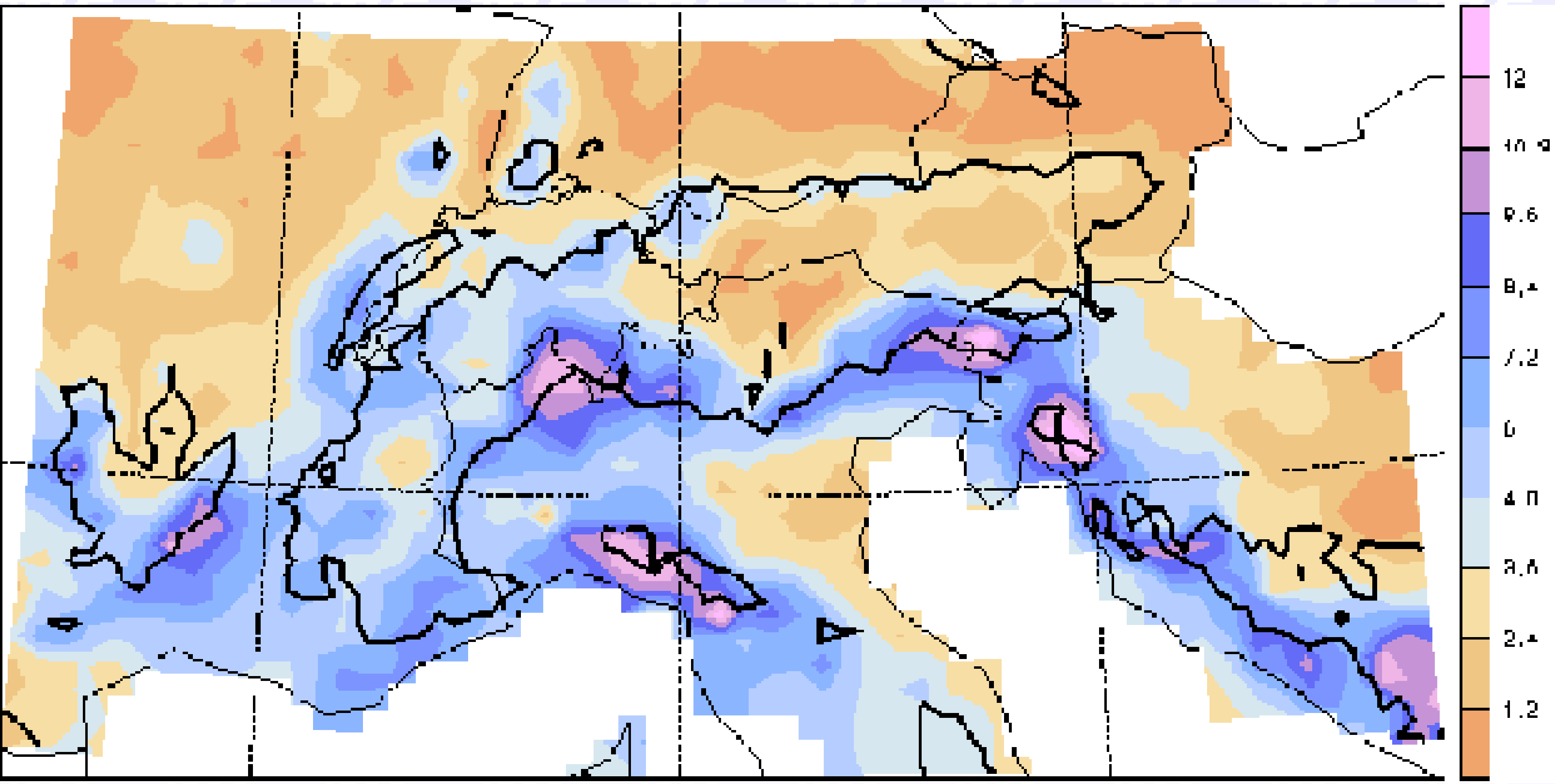


Caracena et al. (1979)

Many-Scaled Topography



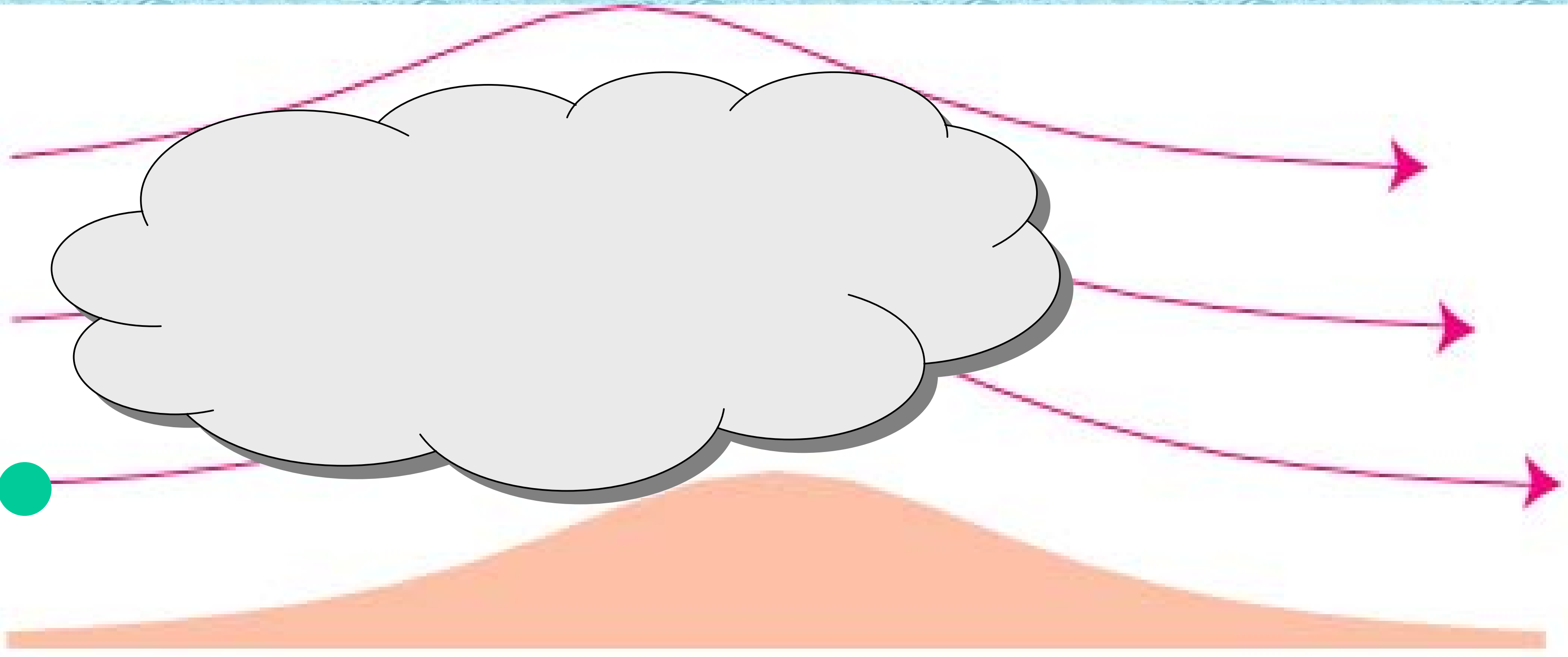
Alpine Precipitation Climatology



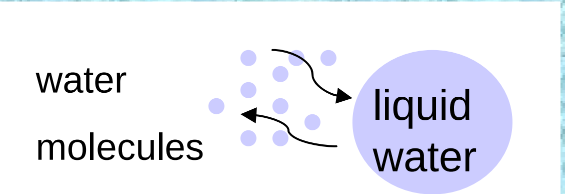
Frei and Schär (1998)

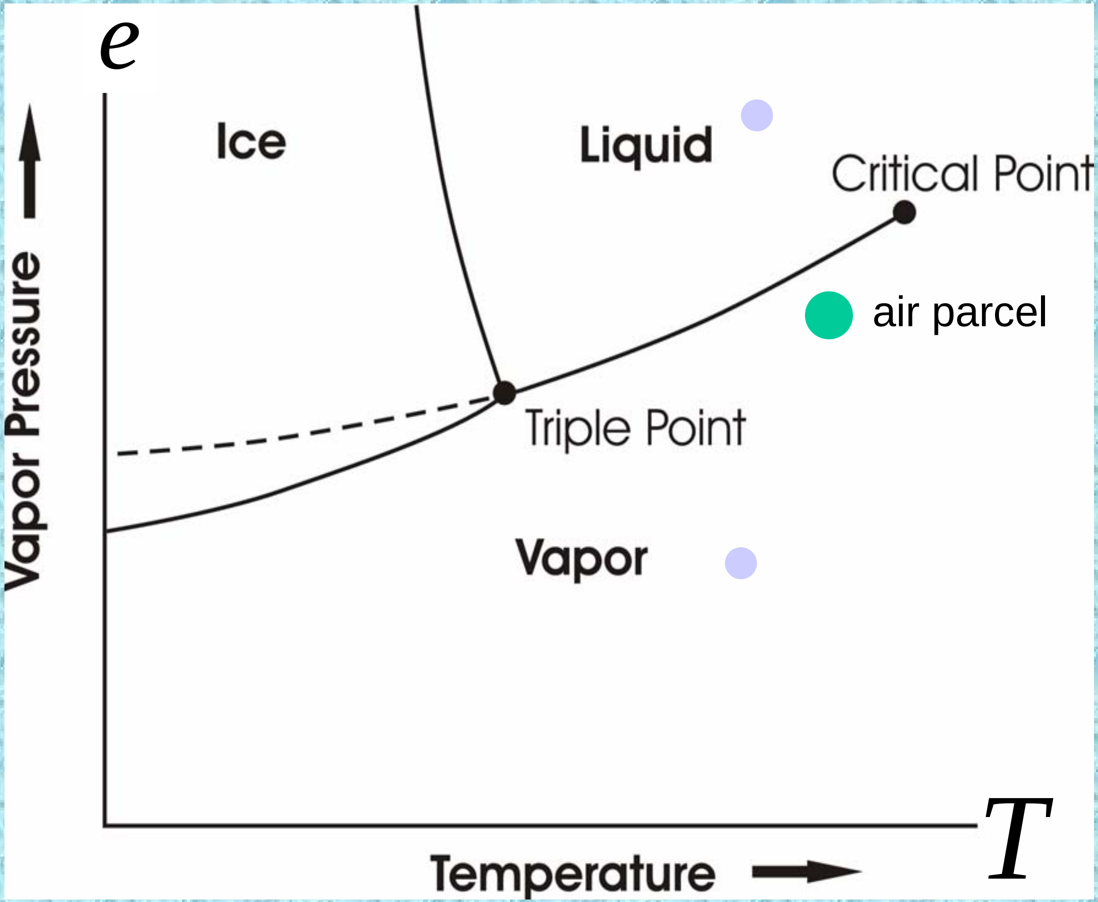
A Little Moist Thermodynamics and Cloud Physics…

Condensation

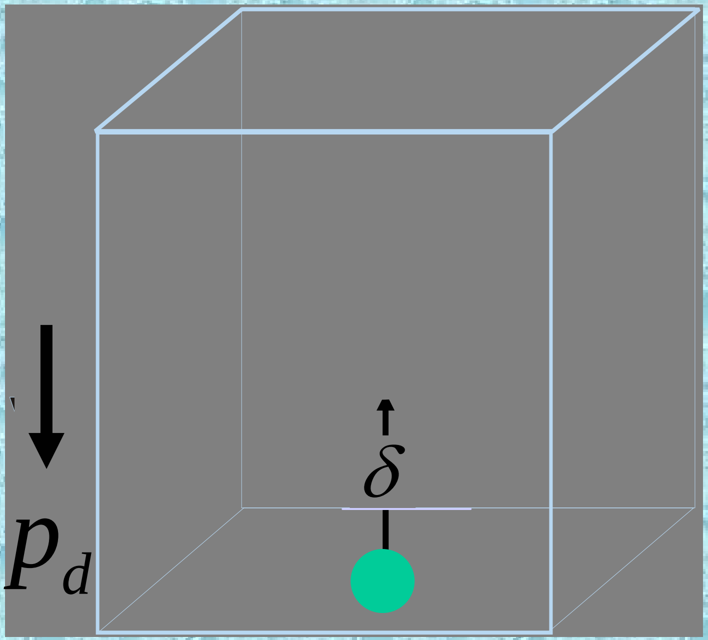


Phase Equilibria





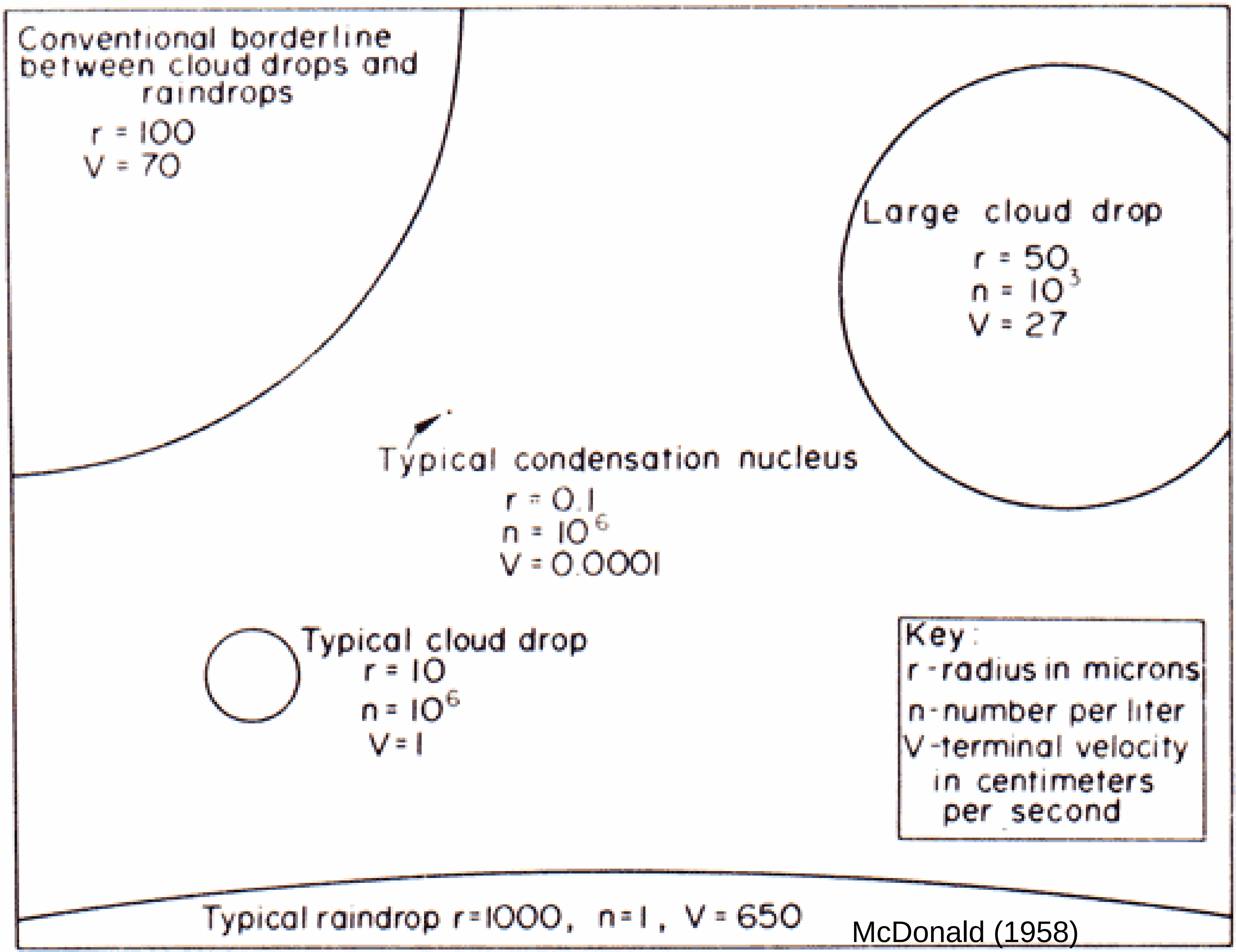
Saturation thru Adiabatic Cooling



$$\frac{\Delta T}{T} = \frac{c_p}{R_d}\frac{\Delta p_d}{p_d} < 0$$

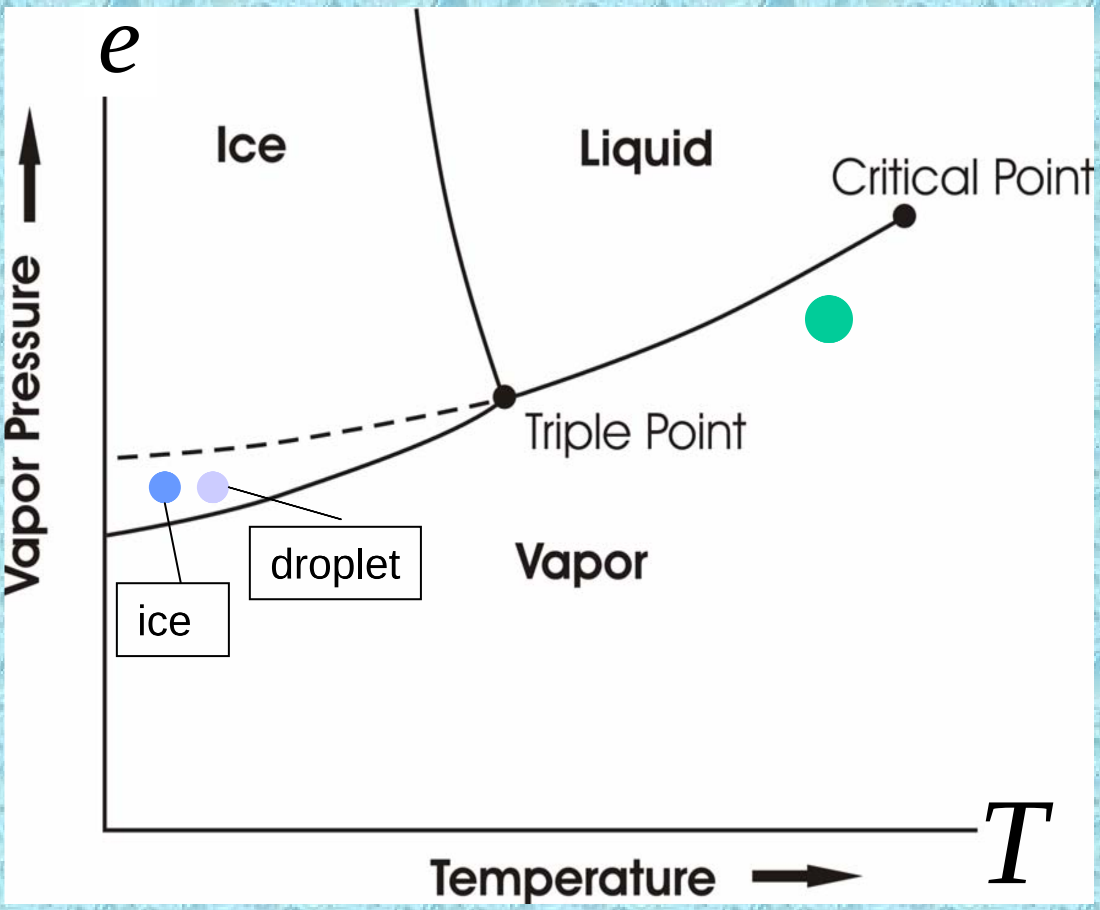
gas law → $\Delta e = \Delta p_d \, q_v \, R_v / R_d$

p_d dry air pressure q_v water vapor mixing ratio

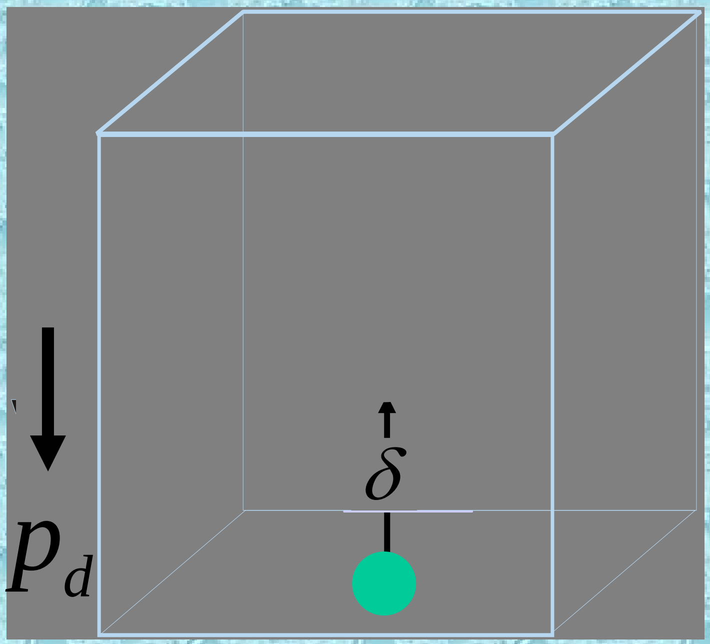


McDonald (1958)

Phase Equilibria



Saturation thru Adiabatic Cooling



$$\frac{\Delta T}{T} = \frac{c_p}{R_d}\frac{\Delta p_d}{p_d} < 0$$

gas law →

$$\Delta e = \Delta p_d \, q_v \, R_v / R_d$$

p_d dry air pressure q_v water vapor mixing ratio

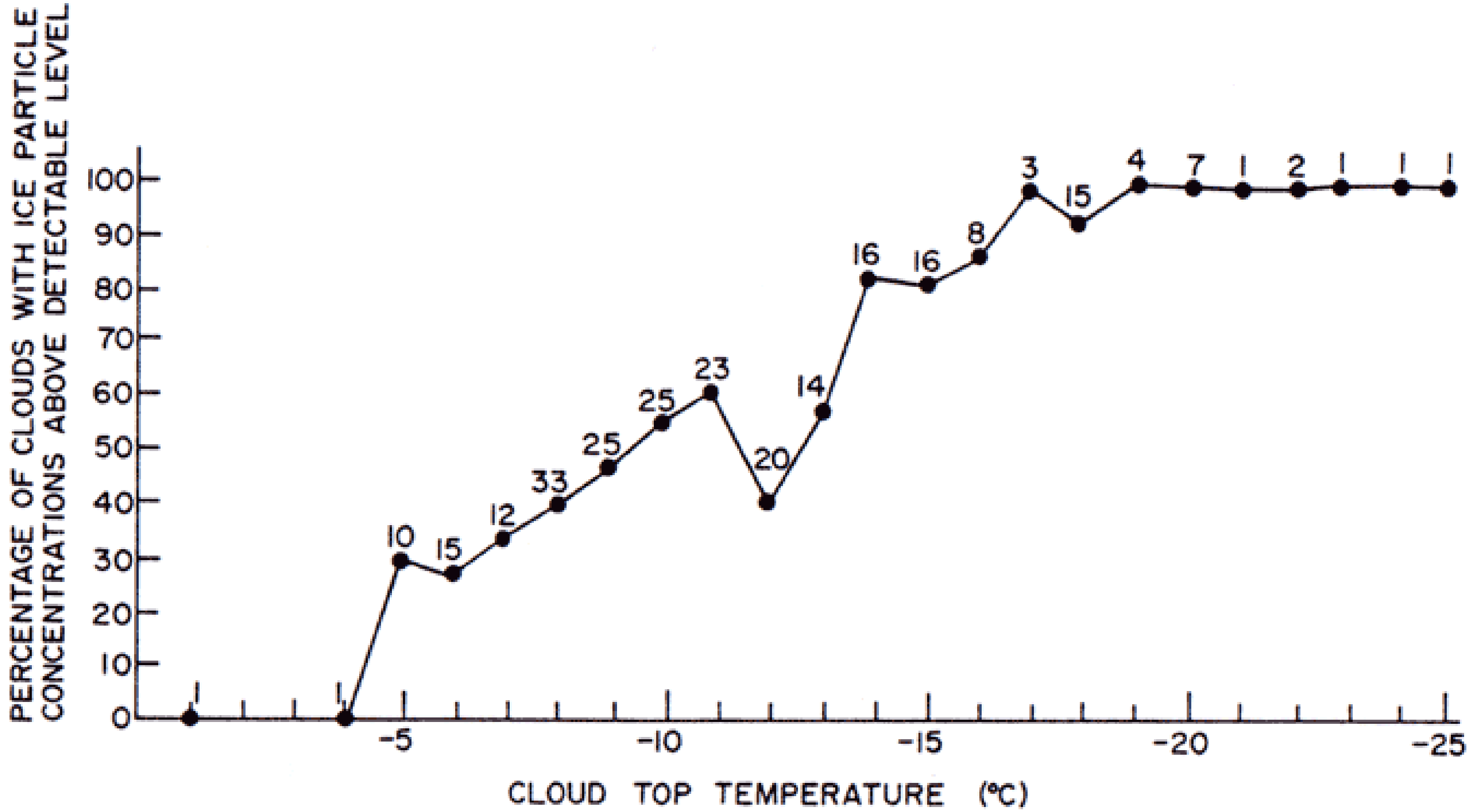
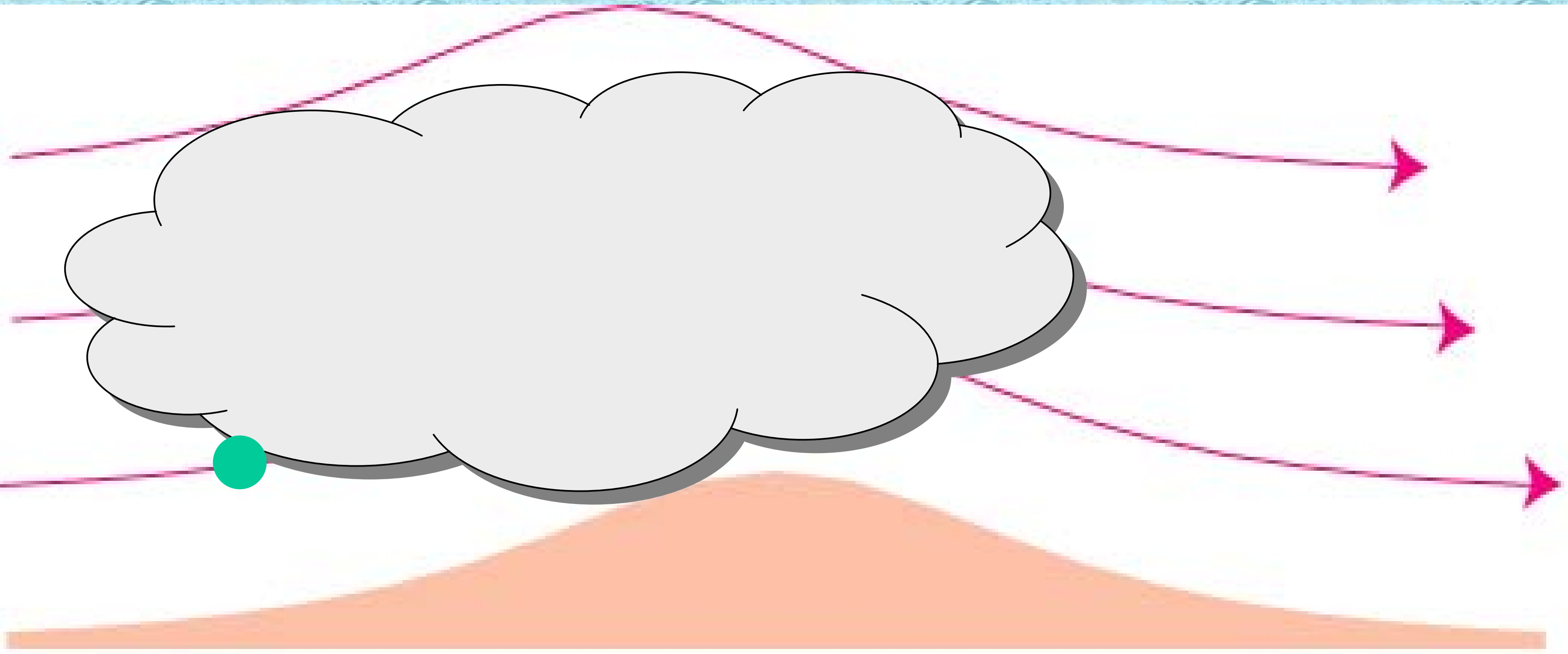


Fig. 4.4 Percentage chance of ice being detected in clouds as a function of the cloud top temperature. Results are based on field observations of 30 orographic cloud systems. The number above each point is the total number of cloud samples for that temperature. [*From* Proc. Amer. Met. Soc. 1st National Conf. on Weather Modification, *Albany, N. Y., 1968, p. 306;* Quart. J. Roy. Met. Soc., **96,** *487 (1970);* Proc. Intern. Conf. on Weather Modification, *Canberra, Australia, 1971, p. 5.*]

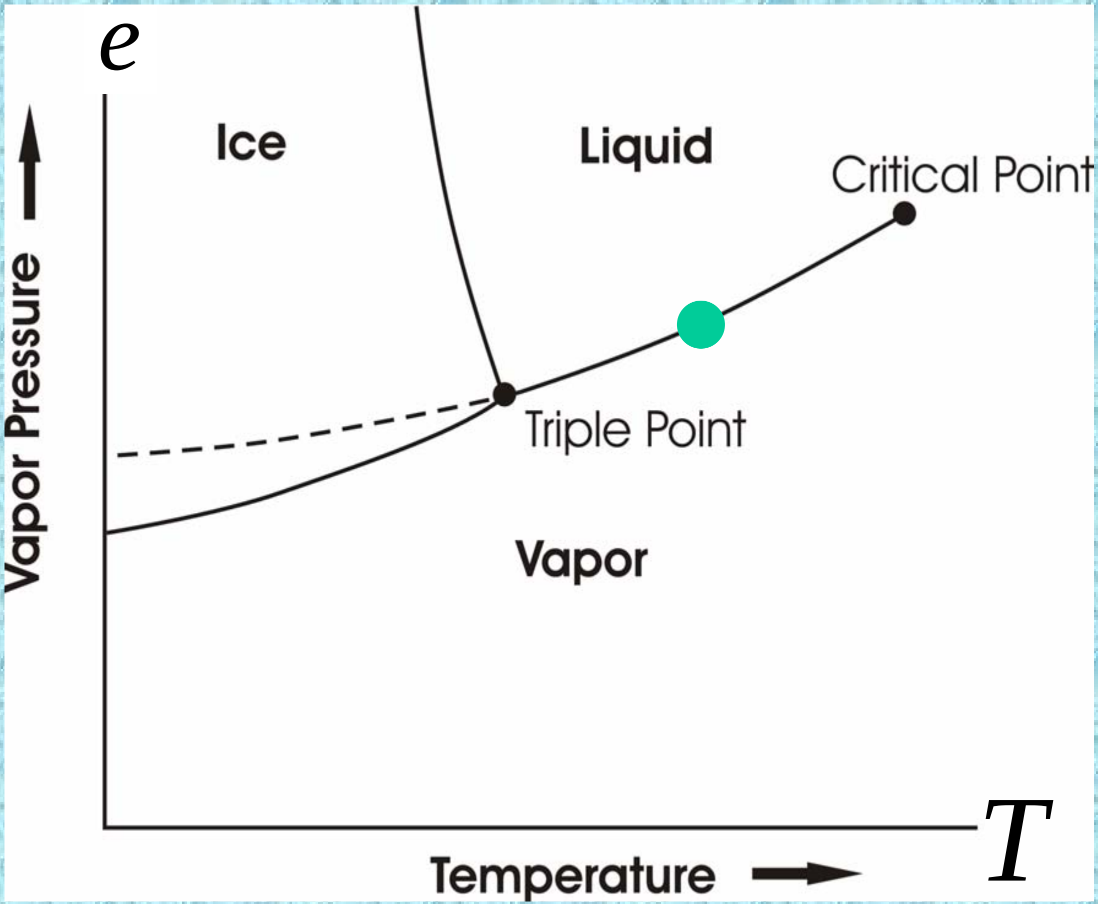
Substance	Crystal lattice dimension: a axis (Å)	Crystal lattice dimension: c axis (Å)	Temperature to nucleate ice (°C)	Comments
Pure substances				
Ice	4.52	7.36	0	—
AgI	4.58	7.49	−4	Insoluble
PbI_2	4.54	6.86	−6	Slightly soluble
CuS	3.80	16.43	−7	Insoluble
CuO	4.65	5.11	−7	Insoluble
HgI_2	4.36	12.34	−8	Insoluble
Ag_2S	4.20	9.50	−8	Insoluble
CdI_2	4.24	6.84	−12	Soluble
I_2	4.78	9.77	−12	Soluble
Minerals				
Vaterite	4.12	8.56	−7	
Kaolinite	5.16	7.38	−9	(Silicate)
Volcanic ash	—	—	−13	
Halloysite	5.16	10.1	−13	
Vermiculite	5.34	28.9	−15	
Cinnabar	4.14	9.49	−16	
Organic materials				
!!! Testosterone	14.73	11.01	−2	
!!! Chloresterol	14.0	37.8	−2	
Metaldehyde	—	—	−5	
β-Naphthol	8.09	17.8	−8.5	
Phloroglucinol	—	—	−9.4	
Bacterium *Pseudomonas Syringae*	—	—	−2.6	(Bacteria in leaf mold)

Rogers and Yau (1991)

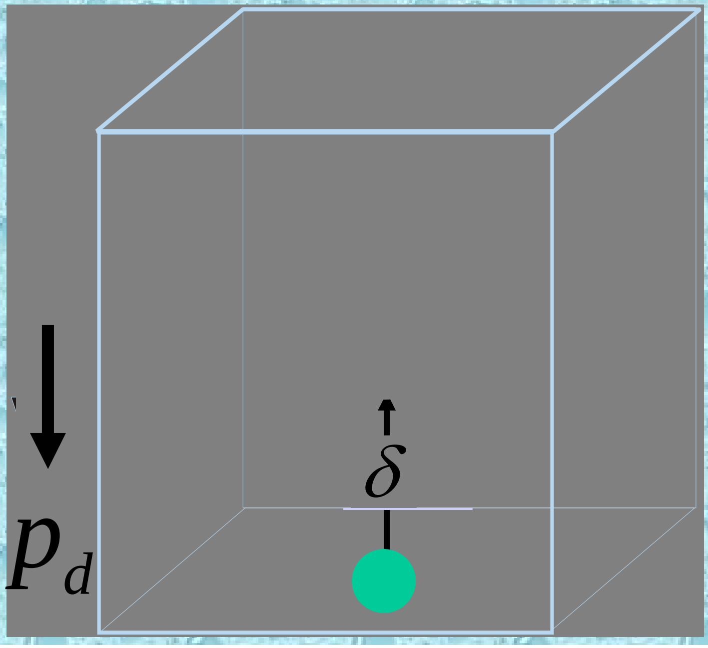
Condensation



Phase Equilibria



Latent Heating Offsets Adiabatic Cooling



$$\frac{\Delta T}{T} = \frac{c_p}{R_d}\frac{\Delta p_d}{p_d} - \frac{L}{Tc_p}\Delta q_{vs}$$

gas law → $q_{vs} = e_s / p_d$

p_d dry air pressure q_v water vapor mixing ratio

Orographic Precipitation Summary

- Large – Scale (Wind, Humidity, Stability)
- Mesoscale dynamics of orographic air flow
- Microphysics