Hydrology of catchments, rivers and deltas (CIE5450)

Prof.dr.ir. Uhlenbrook

Lecture ‘Precipitation’

Hydrology of Catchments, River Basins and Deltas

Part TWO – Precipitation

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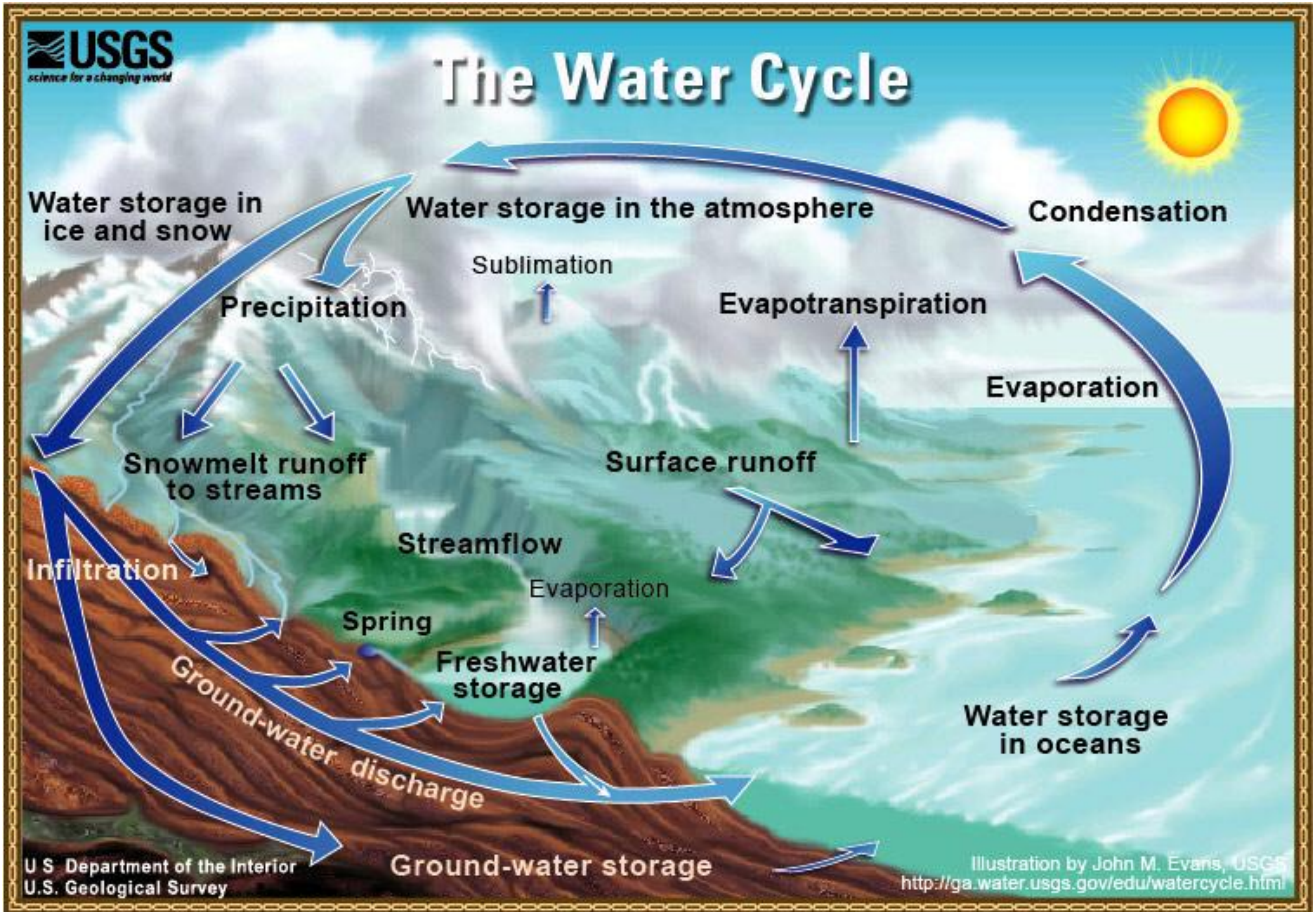
  (some PPT slides and pictures)

Elements of the Hydrological Cycle




Source: Koutsoyiannis and Langousis, 2009

Objectives of this Lecture

- Types of precipitation
- Precipitation formation processes
- Precipitation parameters
- Measurement techniques for precipitation
- Areal estimation of precipitation

Precipitation

- Rain (light - heavy), snow, drizzle, hail, ...

- Formed from water vapor in the atmosphere:
  - Air rises and/or cools (i.e. expansion due to less pressure)
  - Cool air can hold only less water
  - Need of areosols (nuclei for droplets or ice crystals)
  - Excess water forms droplets (mainly in light clouds) or ice crystals (needed for ‘real’ precipitation)

  …. when they are large (heavy) enough, they fall as precipitation!

- Lapse rate (less pressure, expansion, temperature decrease):
  - 0.65 K/100 m (average)
  - dry-adiabatic 1.0 K/100 m
  - wet-adiabatic 0.5-0.6 K/100 m (air is moisture saturated)

Different types of precipitation

Falling precipitation

solid

liquid

Different types of precipitation

‚Intercepted‘ precipitation

solid

liquid

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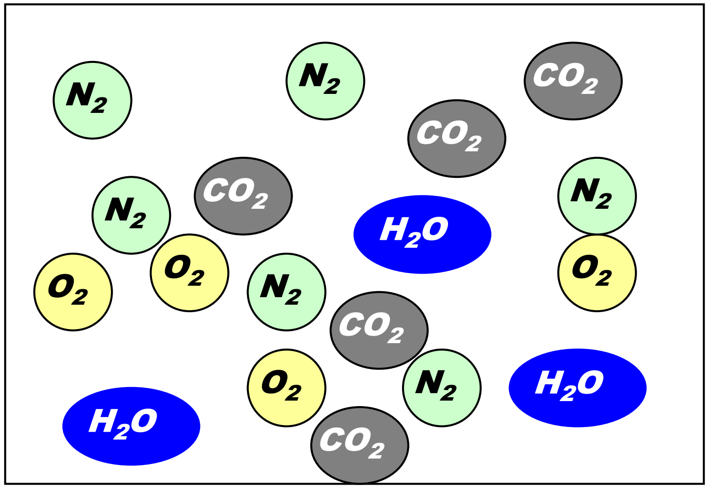
Vapor Pressure

- Partial pressure of H_2O in air is the <u>vapor pressure</u>
- Units of pressure are: Pascals (Pa)
  $M\ L^{-1}\ T^{-2}$: $kg\ m^{-1}\ s^{-2}$
- Also expressed in bars, millibars (mb)

  1 bar = 100,000 Pa = 1×10^5 Pa

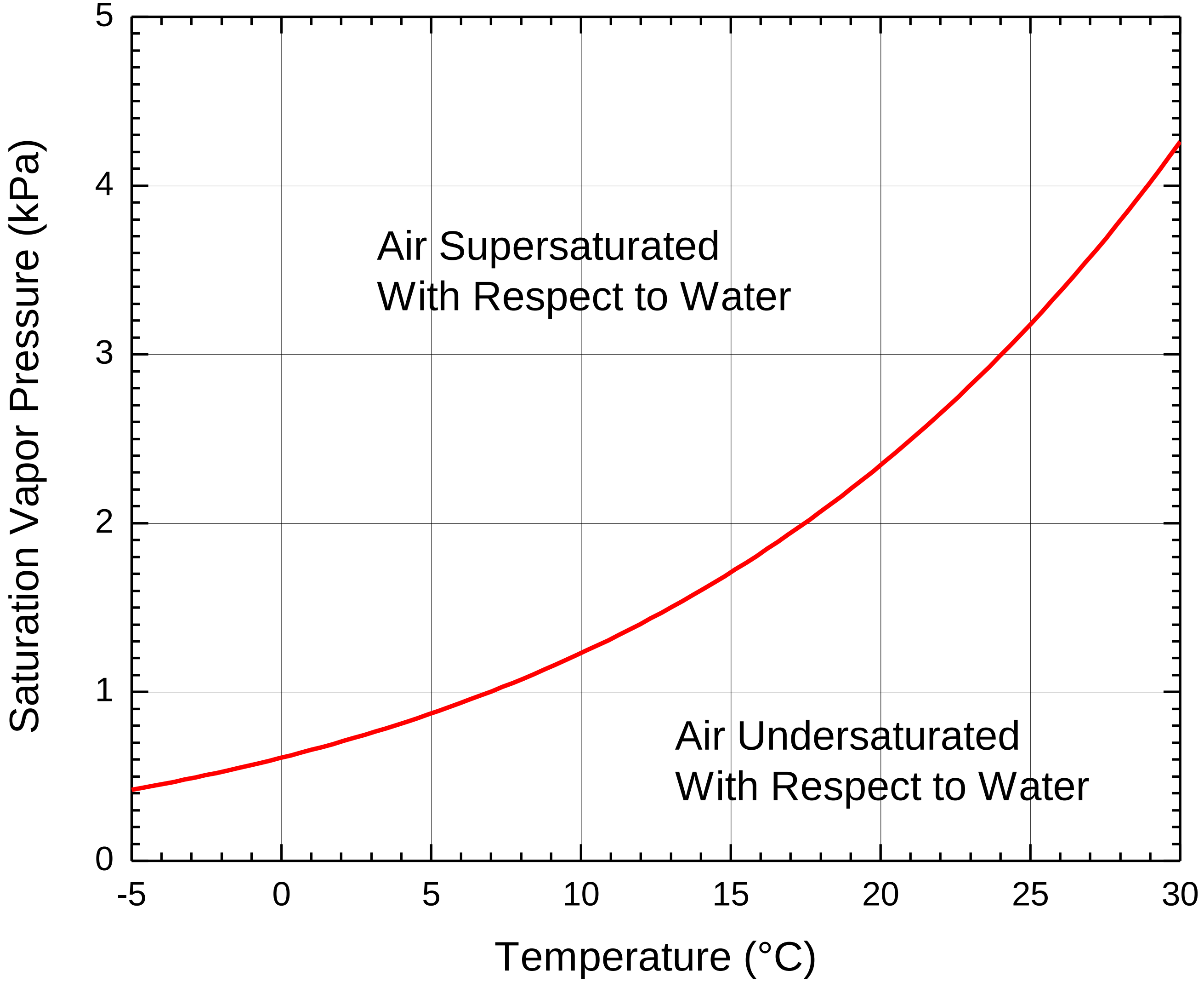
  1 mb = 100 Pa = 1×10^2 Pa
- Less frequently
  – atm, psi, mm Hg, inH_2O



Composition of the atmosphere

	Mass %	**Volume %**
Nitrogen N_2	75.5	78.1
Oxygen O_2	23.1	20.9
Argon A	1.3	0.9
Others	0.1	0.1

Saturation Vapor Pressure – Temperature Relationship



Water damp (gas) (g/m³ air)	**30.4**	**17.3**	**9.4**	**4.9**	**2.2**	**0.9**
Temperature (°C)	**+30**	**+20**	**+10**	**0**	**-10**	**-20**

Saturation Vapor Pressure Curve

Approximated by:

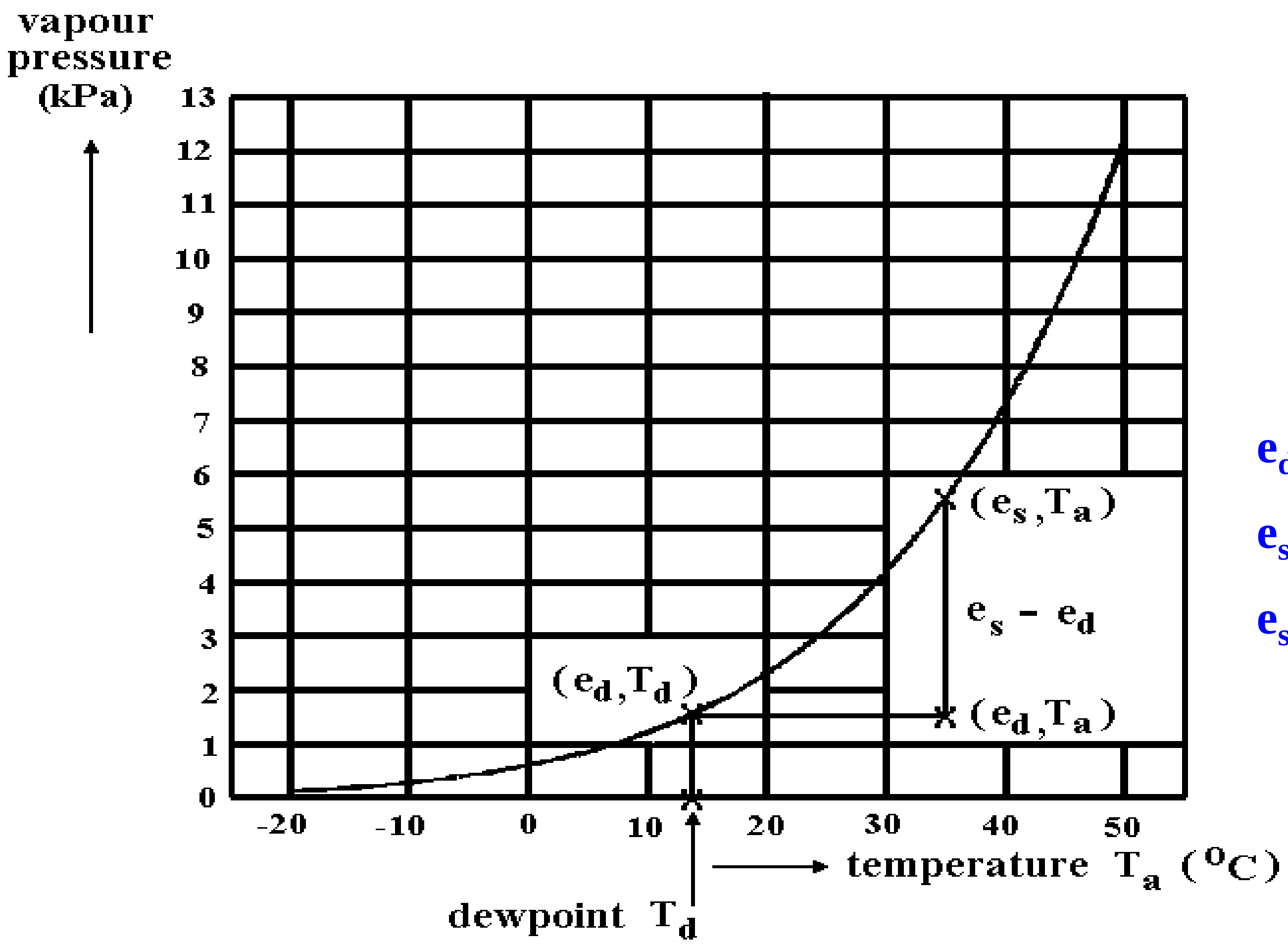
$$e_s = 0.611 \cdot \exp\left(\frac{17.3 \cdot T_s}{T_s + 237.3}\right)$$

$\text{vapor pressure in kPa}$

$\text{temperature in } ^\circ\text{C}$

Or, use vapor pressure tables!

Relation between saturation vapour pressure of the air e_s and air temperature T_a



e_d: dewpoint vapour pressure

e_s: saturation vapour pressure

$e_s - e_d$: Saturation vapour pressure deficit

- Relative humidity [%]: $\mathbf{RH} = \frac{e_d}{e_s} 100$

Measures of Humidity

- Vapor pressure (e_a)
  - partial pressure of H_2O vapor in air
- Relative humidity: $$RH = \frac{e_d}{e_s} 100$$
- Vapor pressure deficit: **es – ed**
- Dew point temperature (T_d):
  - The temperature at which air with a given vapor pressure would be saturated
  - Compute by solving satvp Eqn, or use tables (previous slides)

Note: e_a, T_d are relatively stable in nature, over short time periods !!

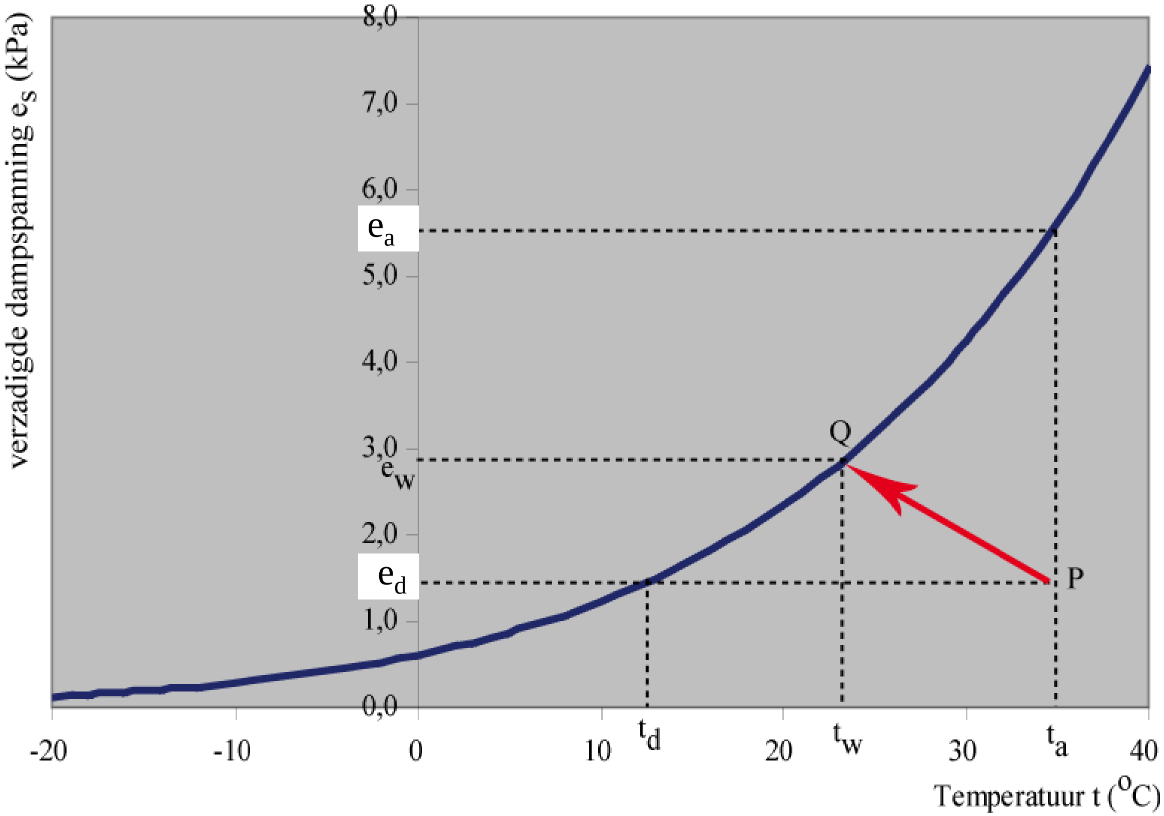
Example Calculation

On a warm summer day, the air temperature is reported to be 29°C with a relative humidity of 40%

- What is the saturated vapor pressure?
- What is the dew point temperature?

In the evening, the temperature drops to 16°C

- What is the relative humidity?



$$e_s(t) = 0.61\exp\left(\frac{17.3t}{237+t}\right)$$

t_a dry bulb temp
t_w wet bulb temp
t_d dew point temp

$$e_d = e_s(t_d) = e_s(t_w) - \gamma(t_a - t_w)$$

γ = psychrometer constant (0.066 kPa/°C)

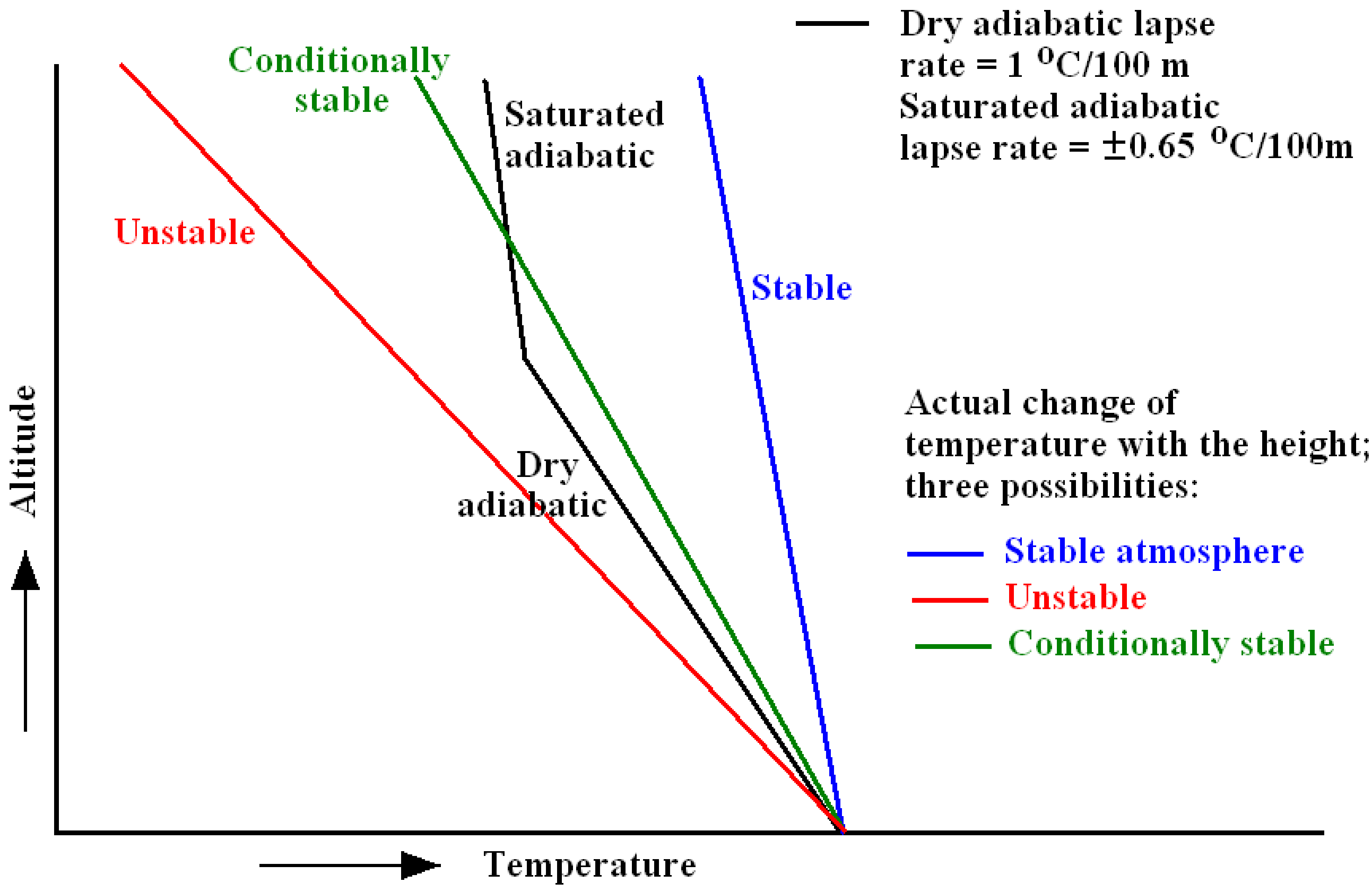
Exercise

Given:
wet bulb temperature t_w= 23 ^oC
dry bulb temperature t_a= 35 ^oC

What is the relative humidity?

1. **calculate $e_s(t_a)$=5.65 kPa**
2. **calculate $e_d=e_s(t_w)-\gamma(t_a-t_w)$**
   =2.82-0.066(35-23)=2.03
3. **RH=2.03/5.65=36%**

Adiabatic lapse rate and the stability of the atmosphere



Remark: change of actual temperature of atmosphere with height is often not linear!

Causes of Precipitation

(Processes that produce uplift of air masses)

- Convection
  - Warm air rises (due to energy input), cools, and forms clouds and potentially thunderstorms
- Fronts
  - E.g. warm, wet air (lighter, above) front rides over cold dry air (heavier, beneath)
- Orography – induced by mountains
  - Warm, moist air rises over mountains and releases water
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- Convergence – occurs in tropics, ITCZ
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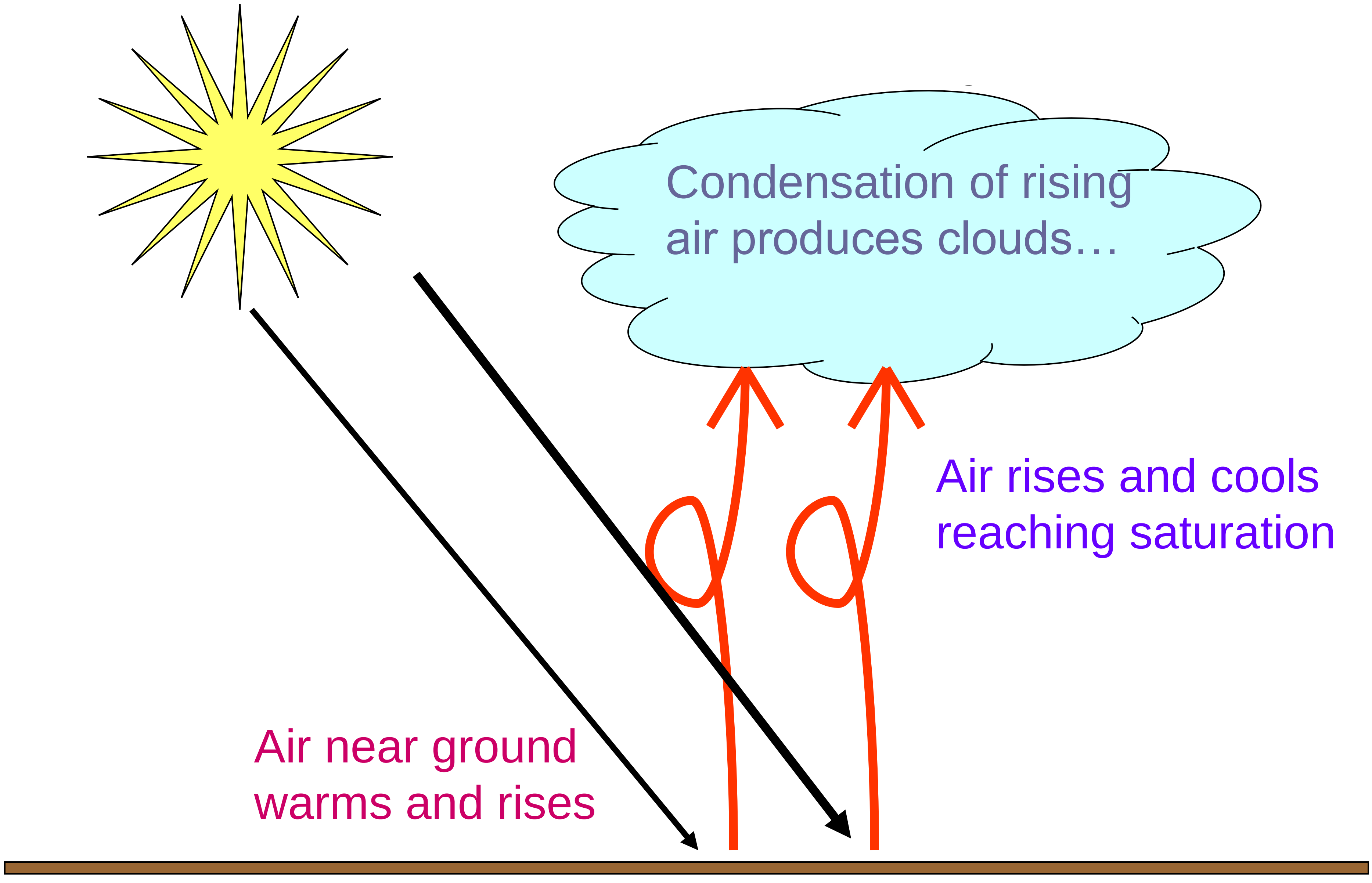
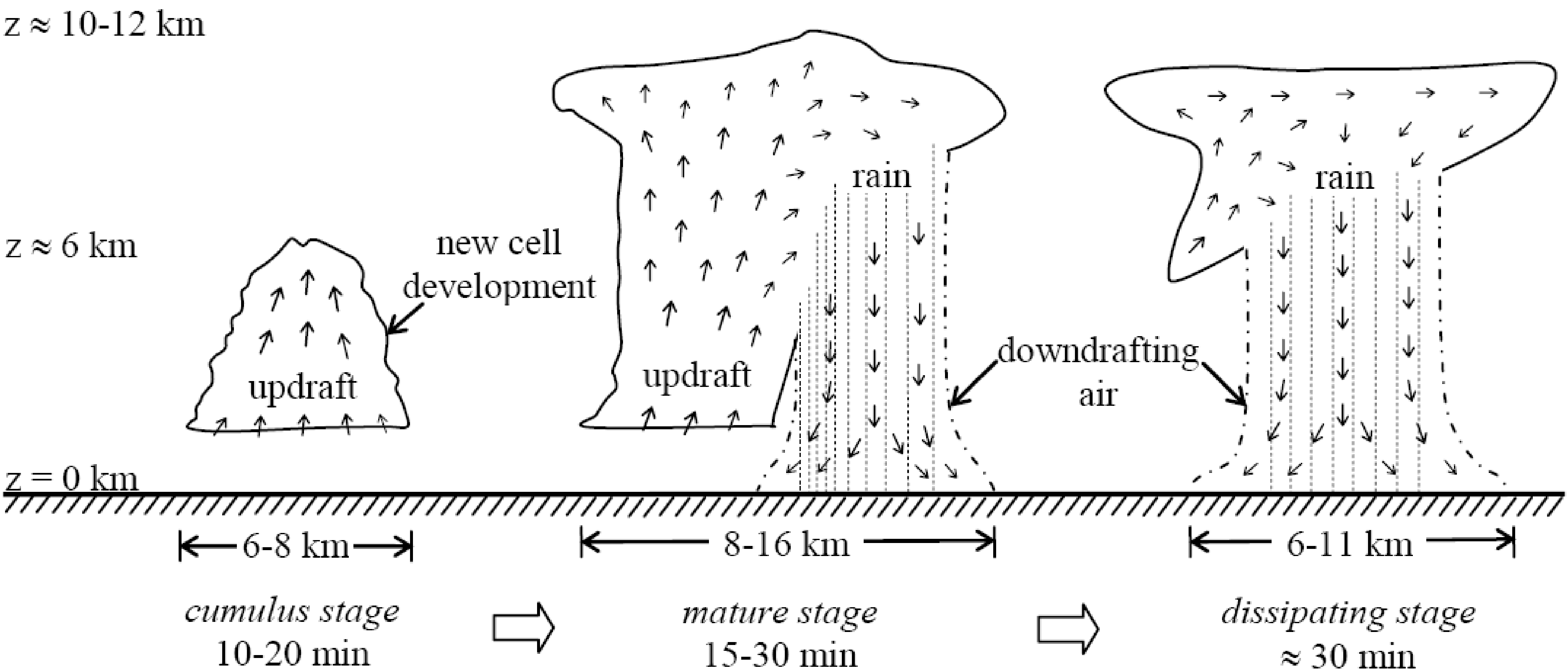
Formation of a convective storm



Stages of development of convective cells

(from Koutsoyiannis and Langousis, 2009; adapted from Weisman and Klemp, 1986)



Source: NOAA Photo Archives

Convective Storms

(picture from prof. Taikan Oki, Japan, 2001)

Convective Storms

Air rises (vertical instability), cools, condensation, precipitation

- Form - rain, hail
- High Intensity, may exceed 40 mm/hr
- Duration - short (minutes to hours)
- Scale - ~1-10s km
  - Common in the tropics, or during summer in temperate zone
  - Can produce flash floods
  - Lightning

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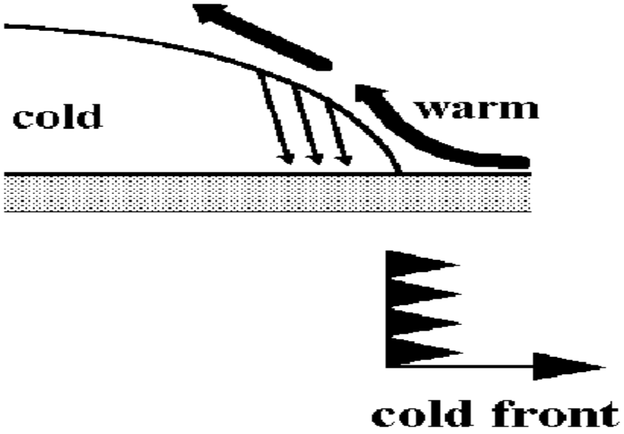
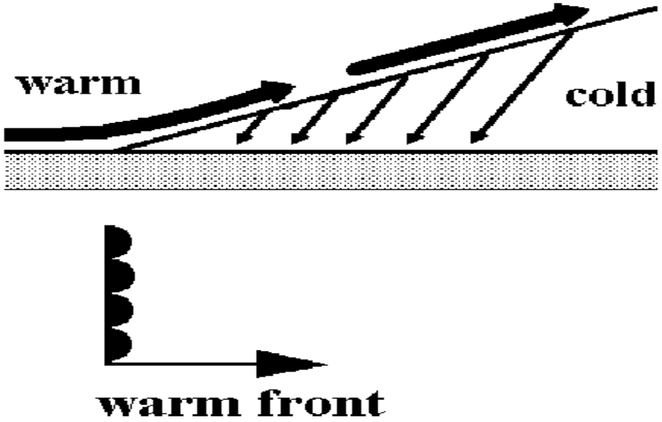
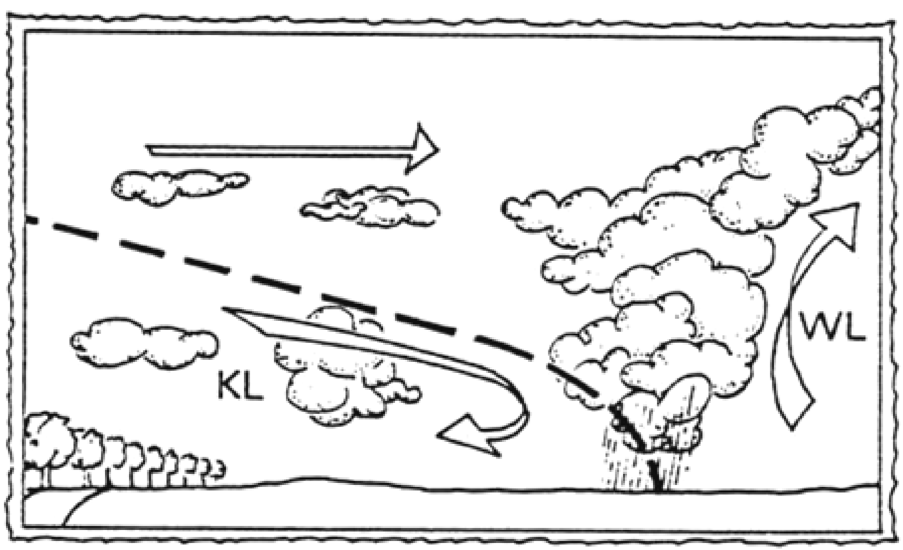
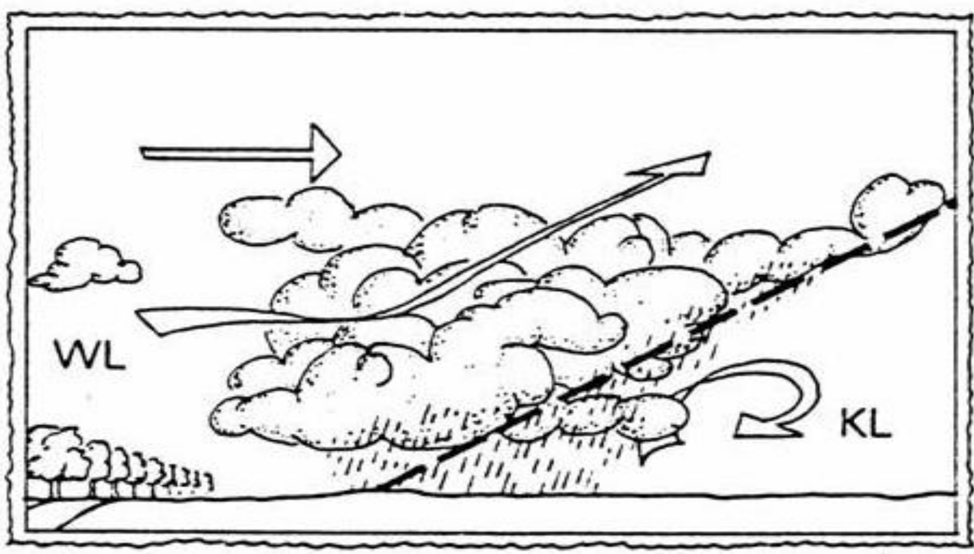
Frontal Precipitation



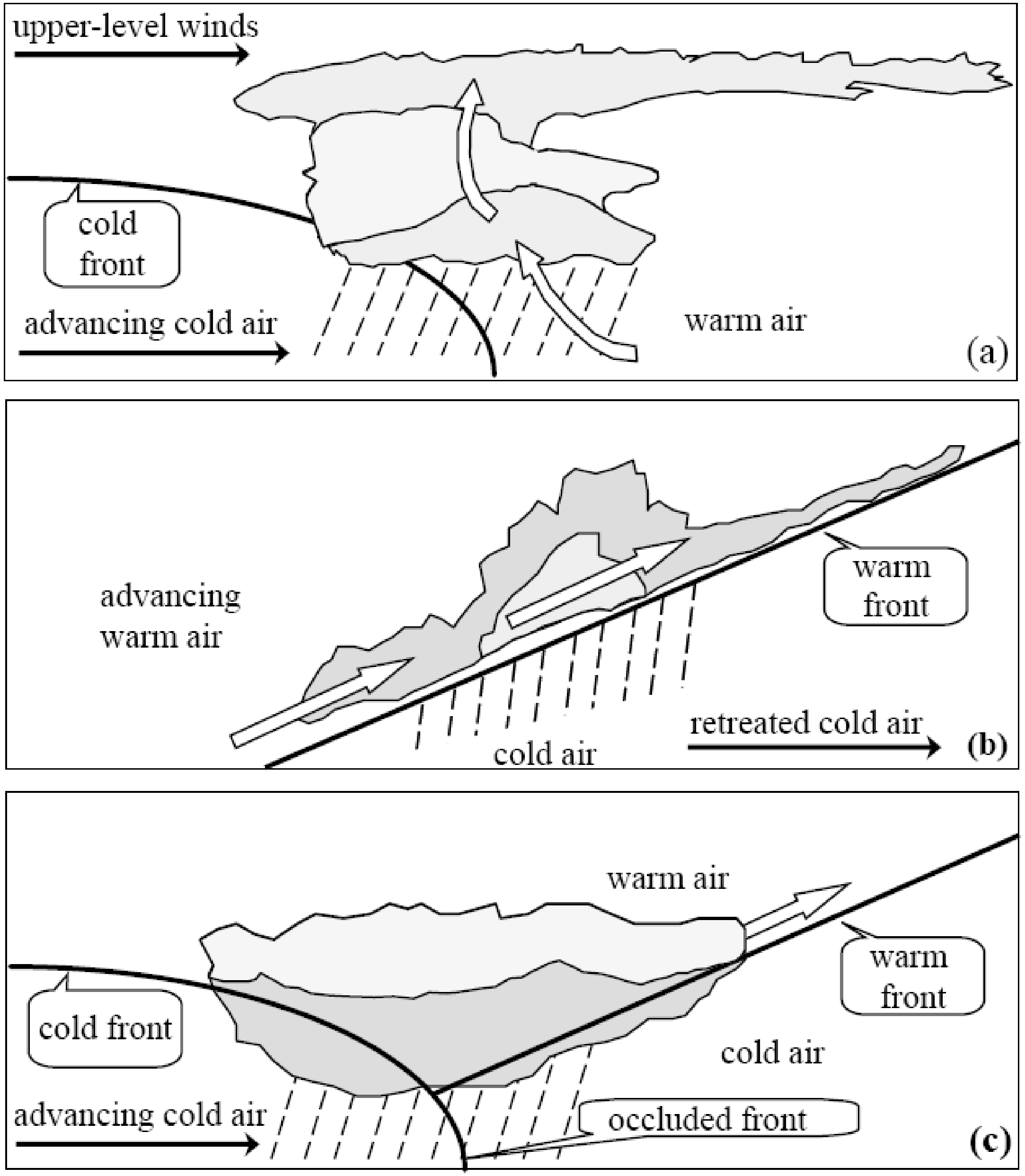


Frontal lifting of air masses





Schematic illustration of different types of fronts: a) cold front, b) warm front, and c) occluded front



(Koutsoyiannis and Xanthopoulos, 1999)

Frontal Precipitation

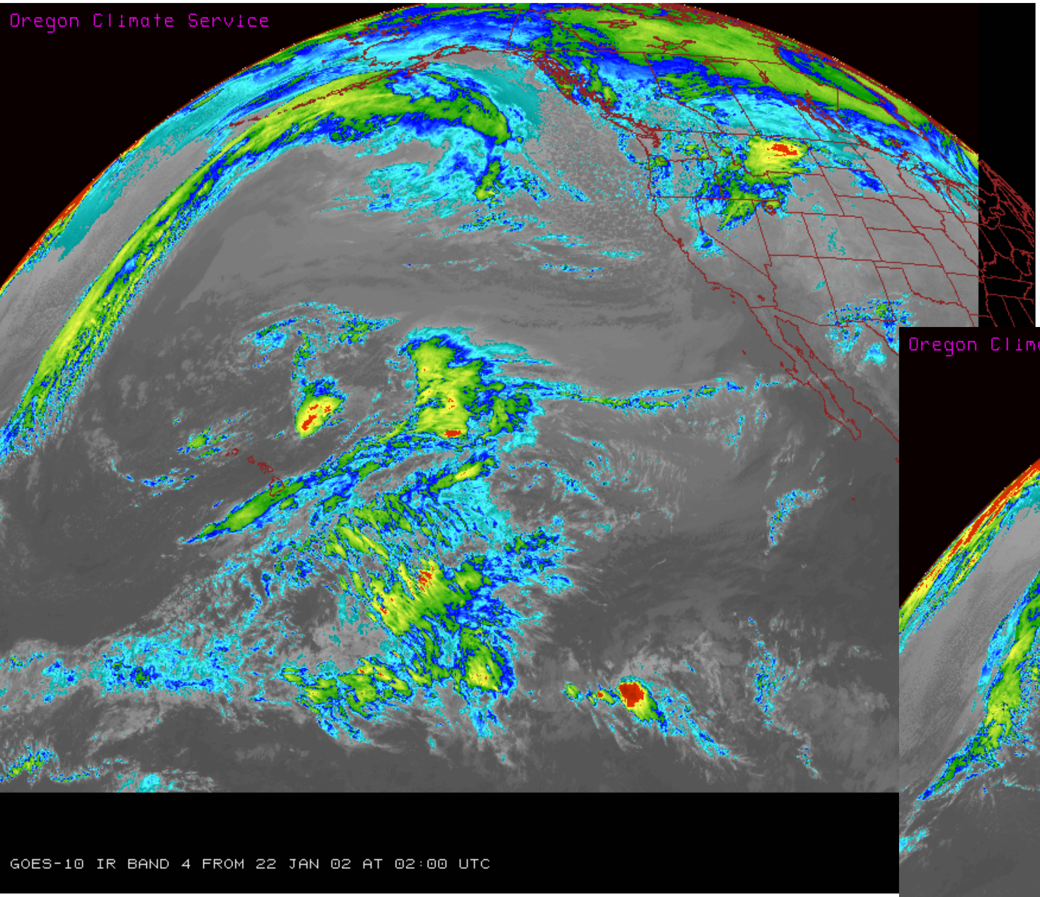
Very common in humid temperate zone (west wind zone), in particular during fall, winter and spring

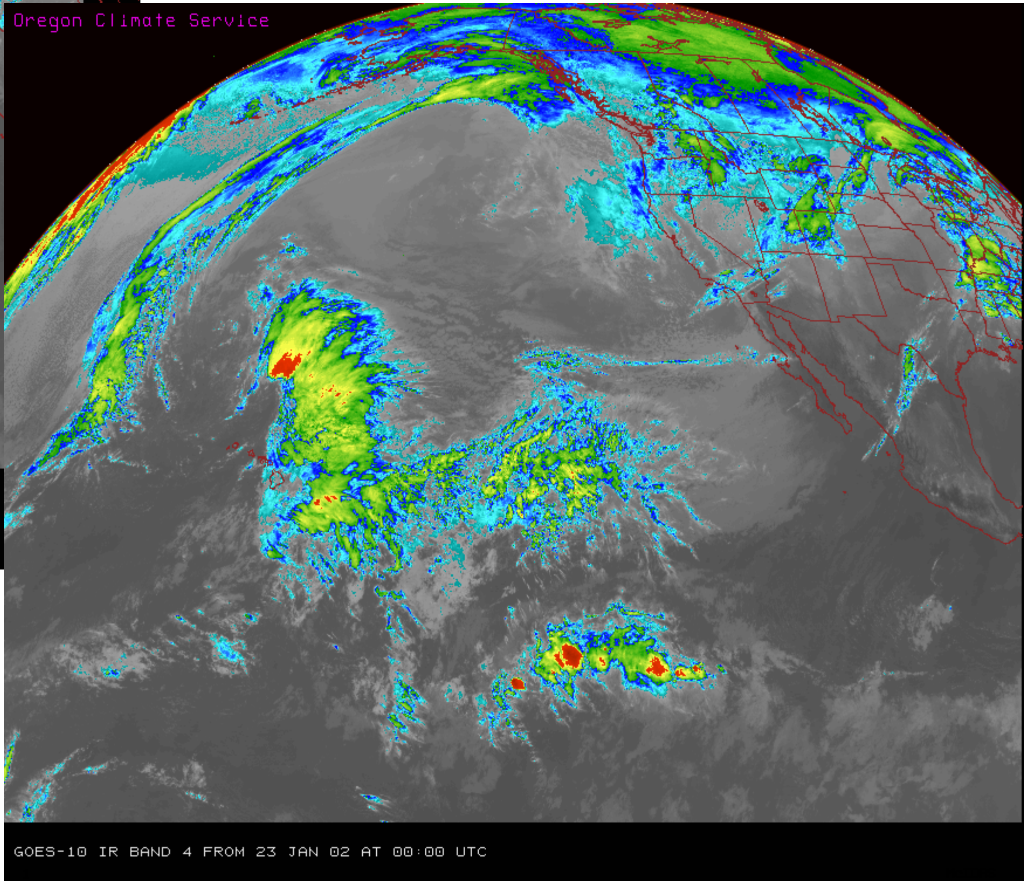
- Form - rain or snow
- Intensity – generally low to moderate ~10 mm/h or less
- Duration - long (hours to days)
- Scale - >100 km

A front comes in ….

North Pacific Satellite Images

Mon. - Tues Jan 21-22, 2002





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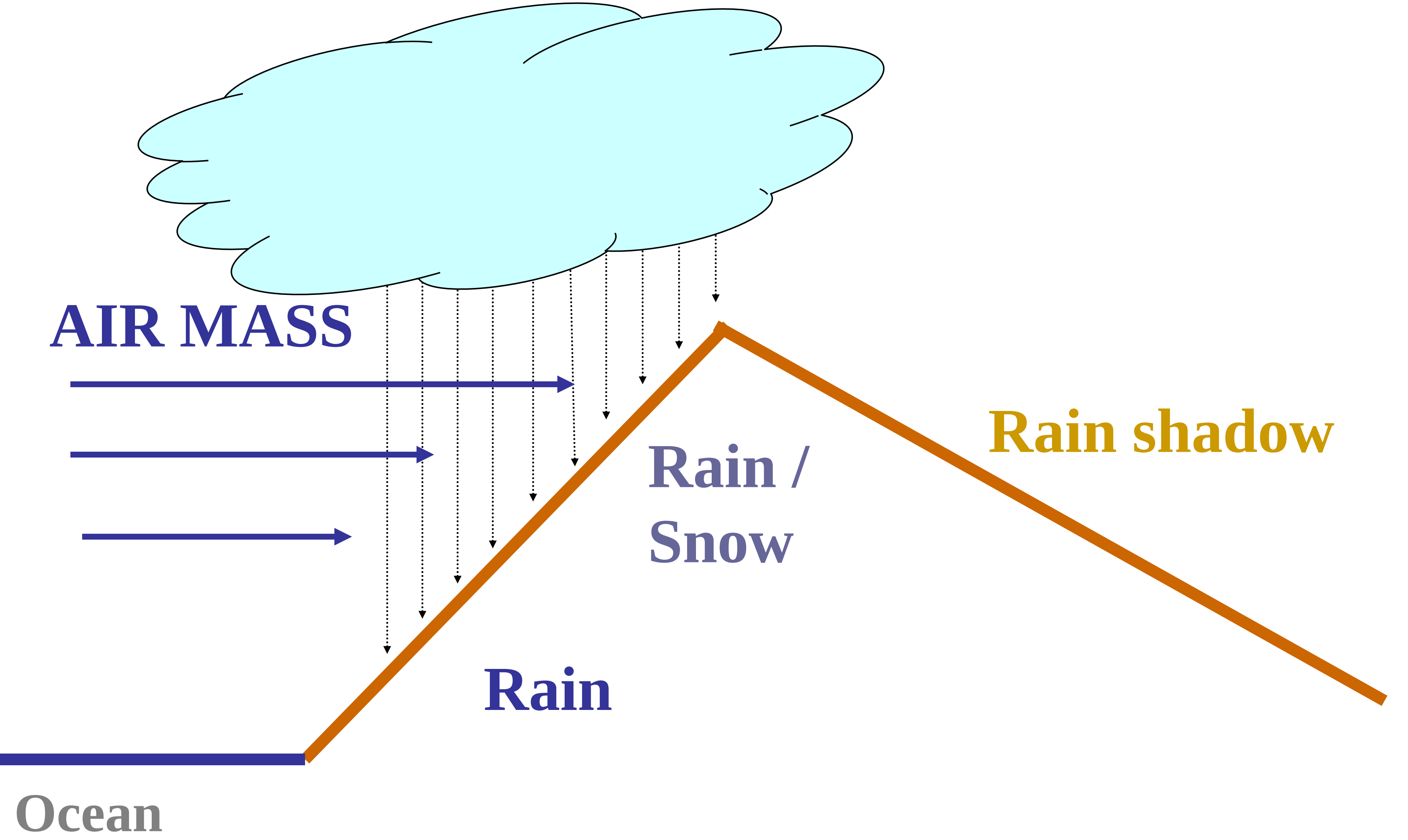
Orographic Precipitation



Example

Orographic precipitation is difficult to catch with a picture …

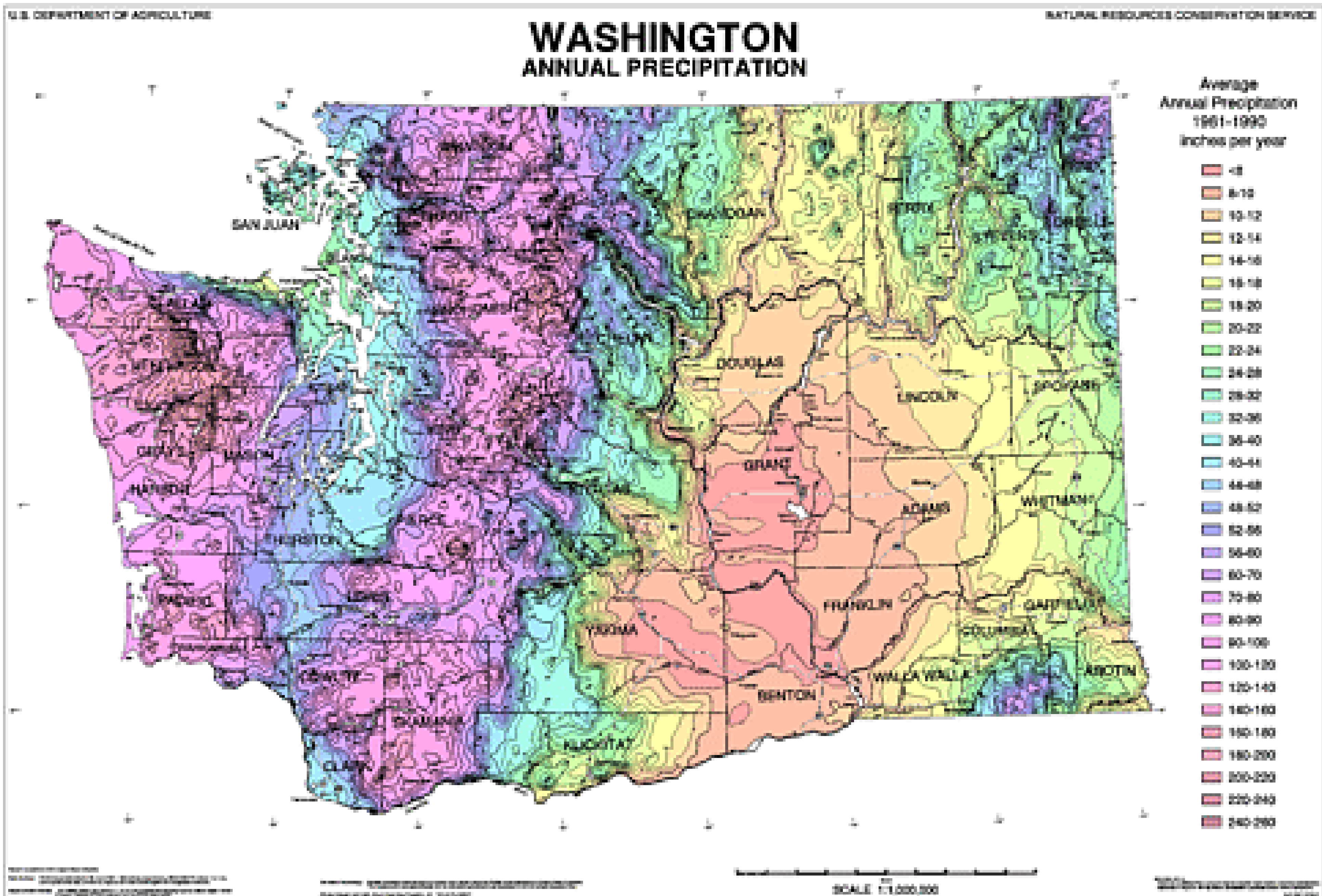
In the rain shadow!

Orographic Precipitation

Common in mountainous regions, sometimes connected to frontal systems

- Form - rain or snow
- Intensity - low to moderate ~10 mm/h; high intensities when sharp rise of the mountains
- Duration - long (hours to days); shorter if additional convection
- Scale - >10-100 km

Example: State of Washington, USA, Annual Precipitation Distribution



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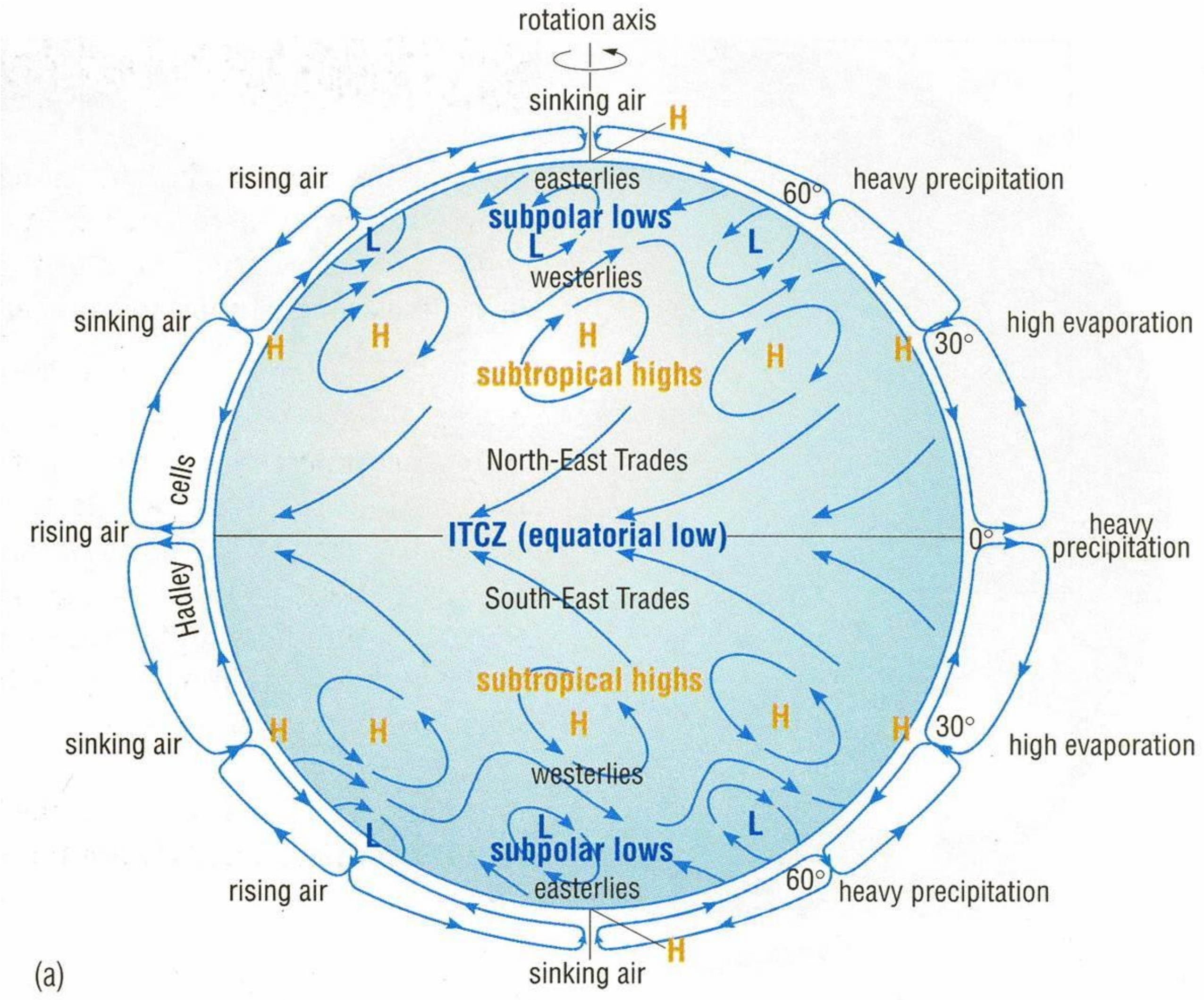
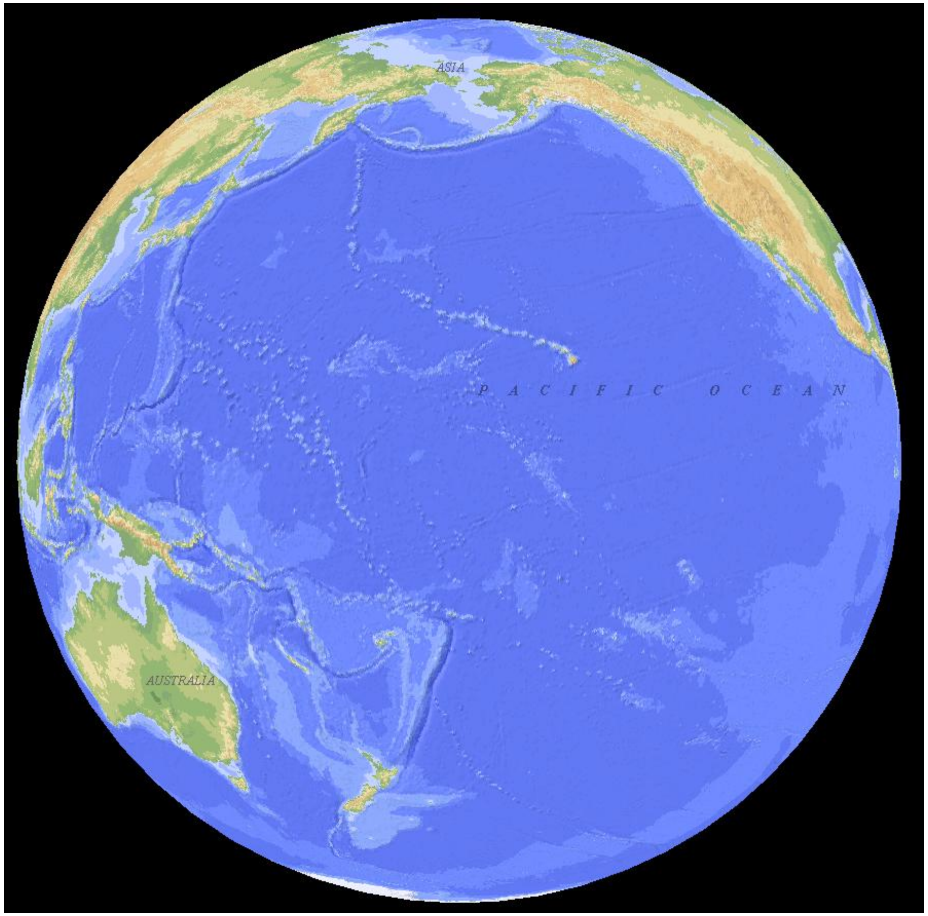
Precipitation through convergence at ITCZ

Wind system for a hypothetical water-covered Earth



Views of the Planet Earth



Precipitation through convergence at ITCZ

- Monsoon

- defines rainy / dry seasons

- one or two rain seasons depending on ITCZ movement

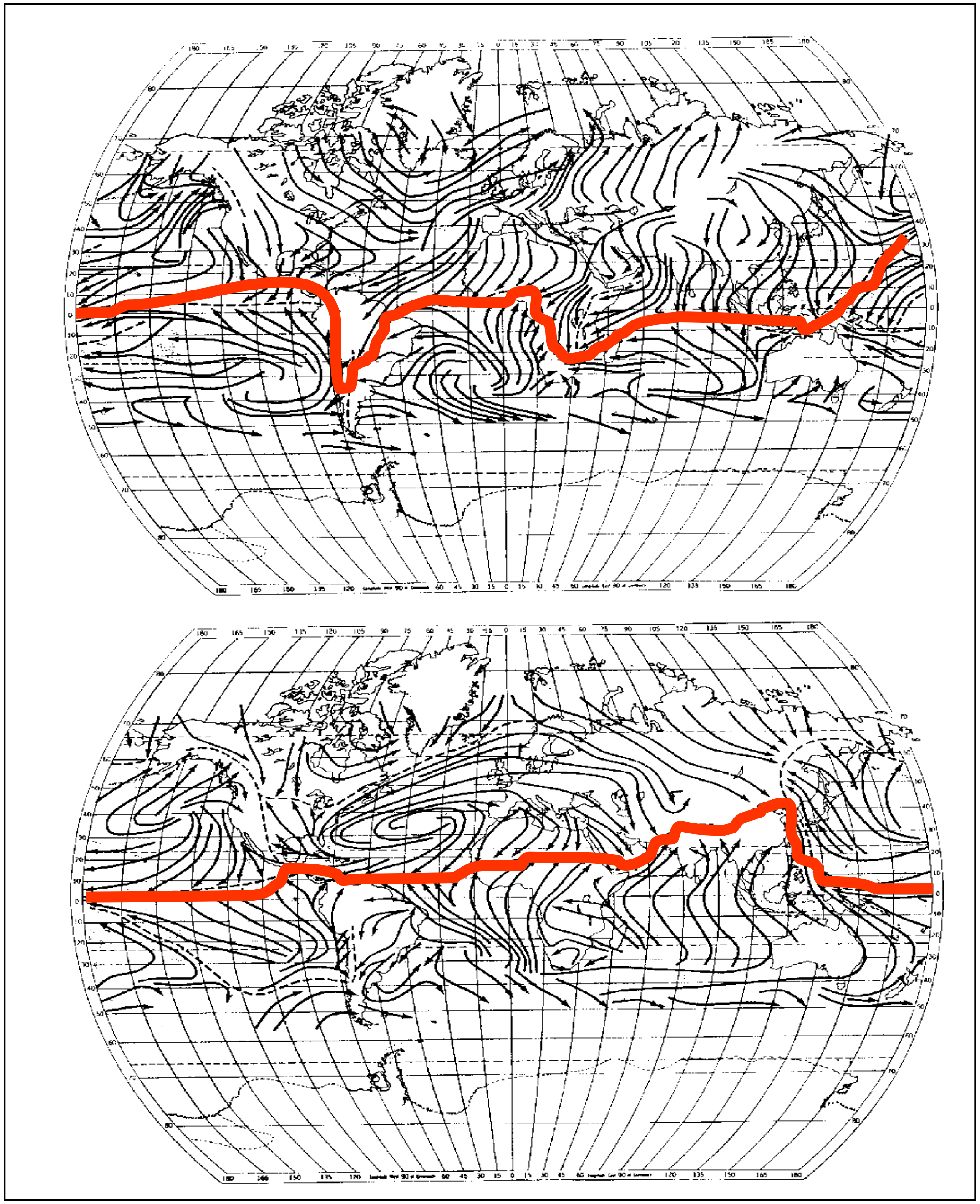
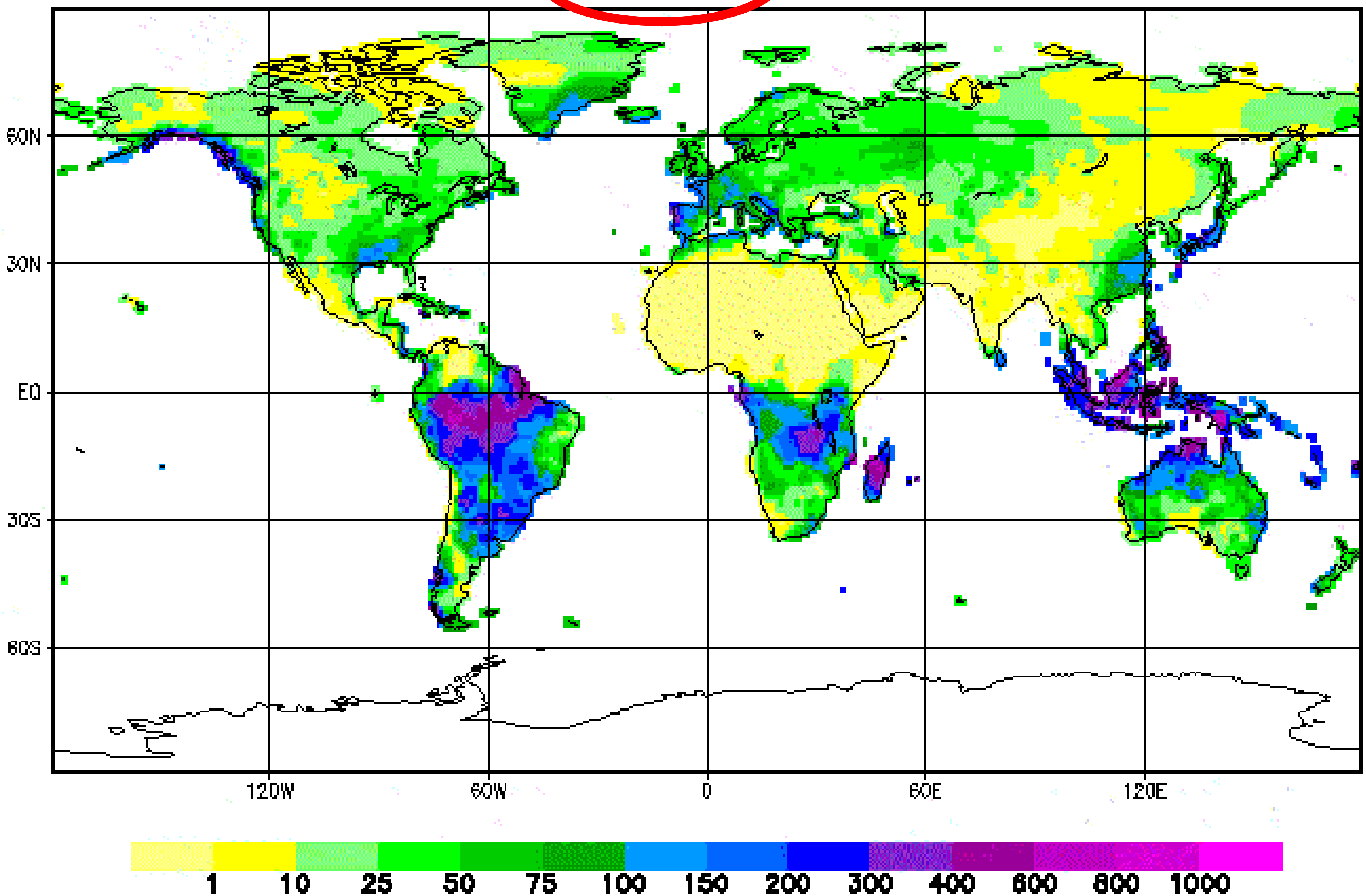


Fig. 2.3 Position of the Inter-Tropical Convergence Zone in January (top) and July (below)

GPCC Monitoring Product Gauge-Based Analysis 1.0 degree
precipitation for January 2001 in mm/month



GPCC

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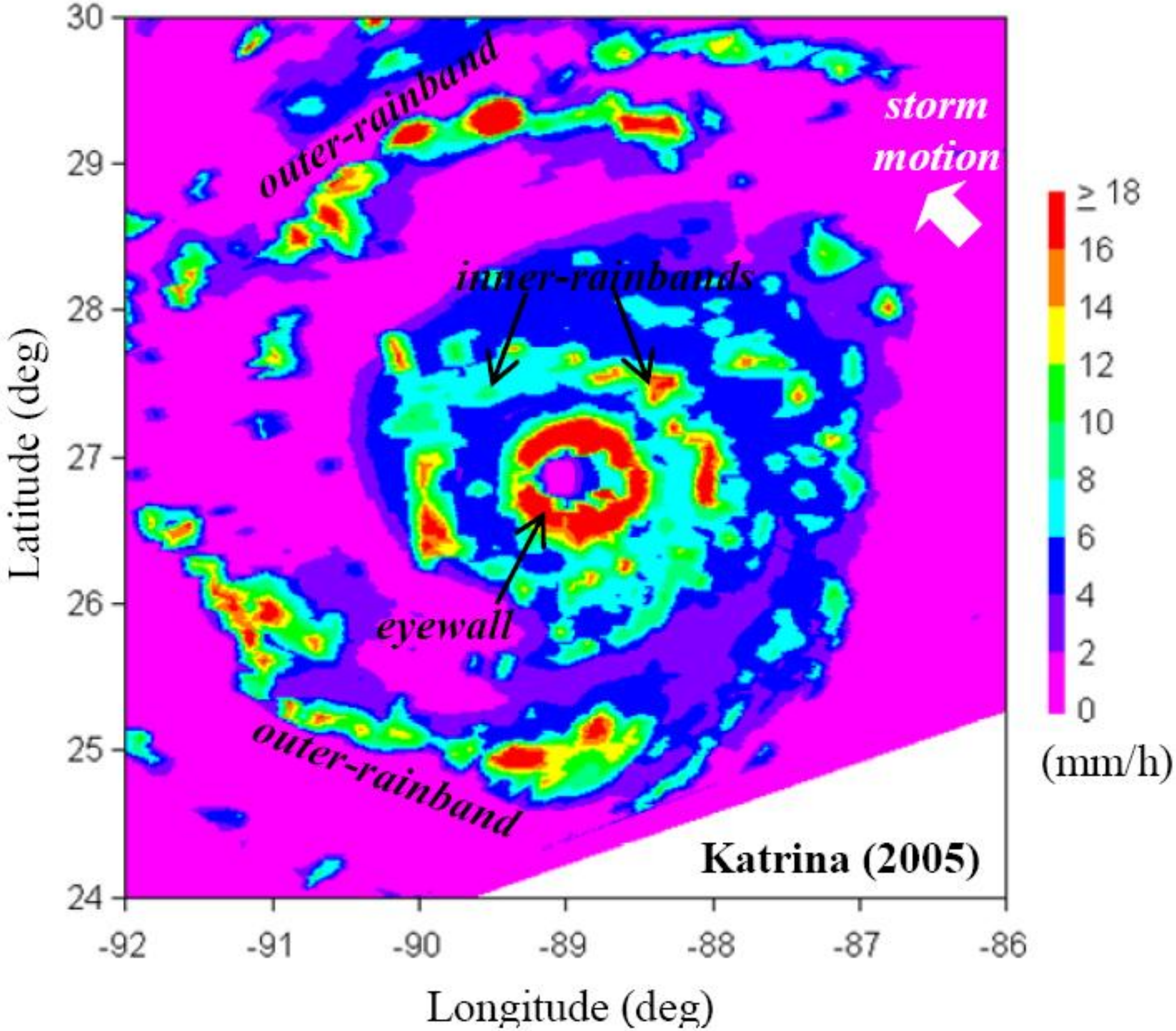
Cyclones, tropical depressions or hurricanes

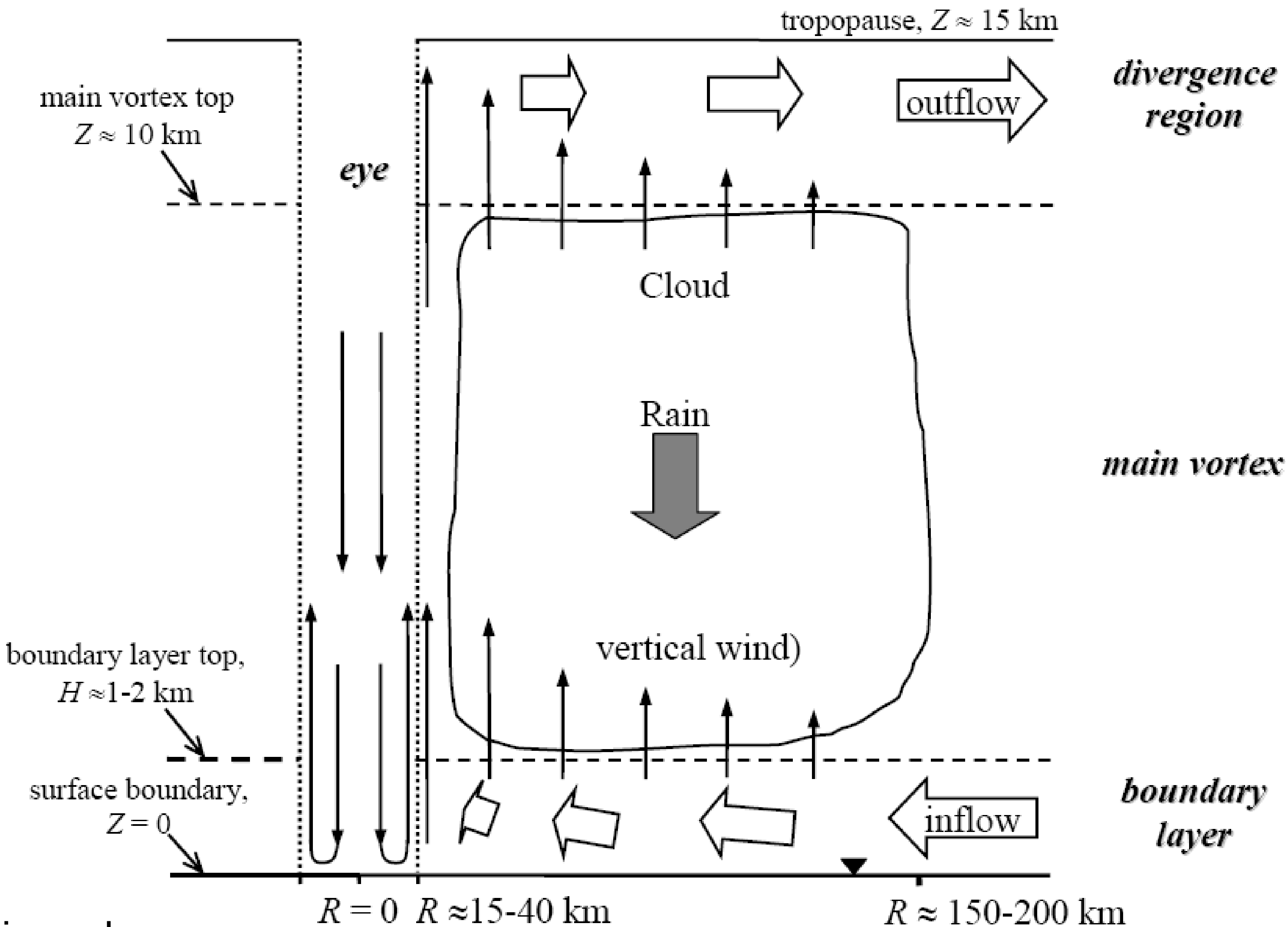
- Active depressions moving over warm ocean water; taking up moisture and energy
- Can cause high intensity rainfall for relatively long times
- Often follow different probability distribution in statistical analysis (extreme value statistics; mixed distributions)

TRMM microwave imager (TMI) rainfall retrievals for hurricane Katrina on 28 August 2005 at 21:00 UTC (frame 44373): Different types of rain bands and their location relative to the centre of the storm

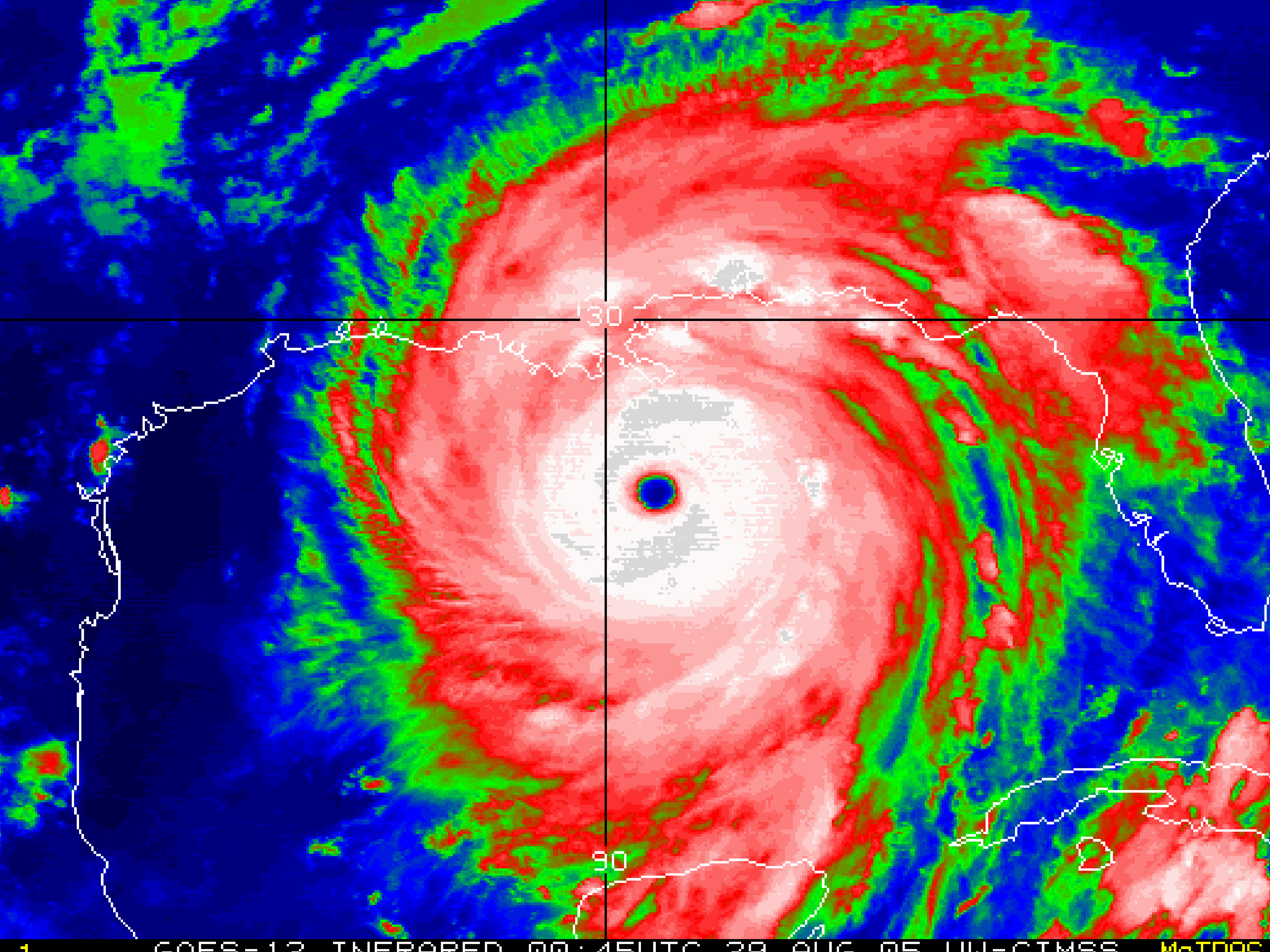


(Koutsoyiannis and Langousis, 2009)

Schematic representation of the structure of a mature hurricane



(Koutsoyiannis and Langousis, 2009)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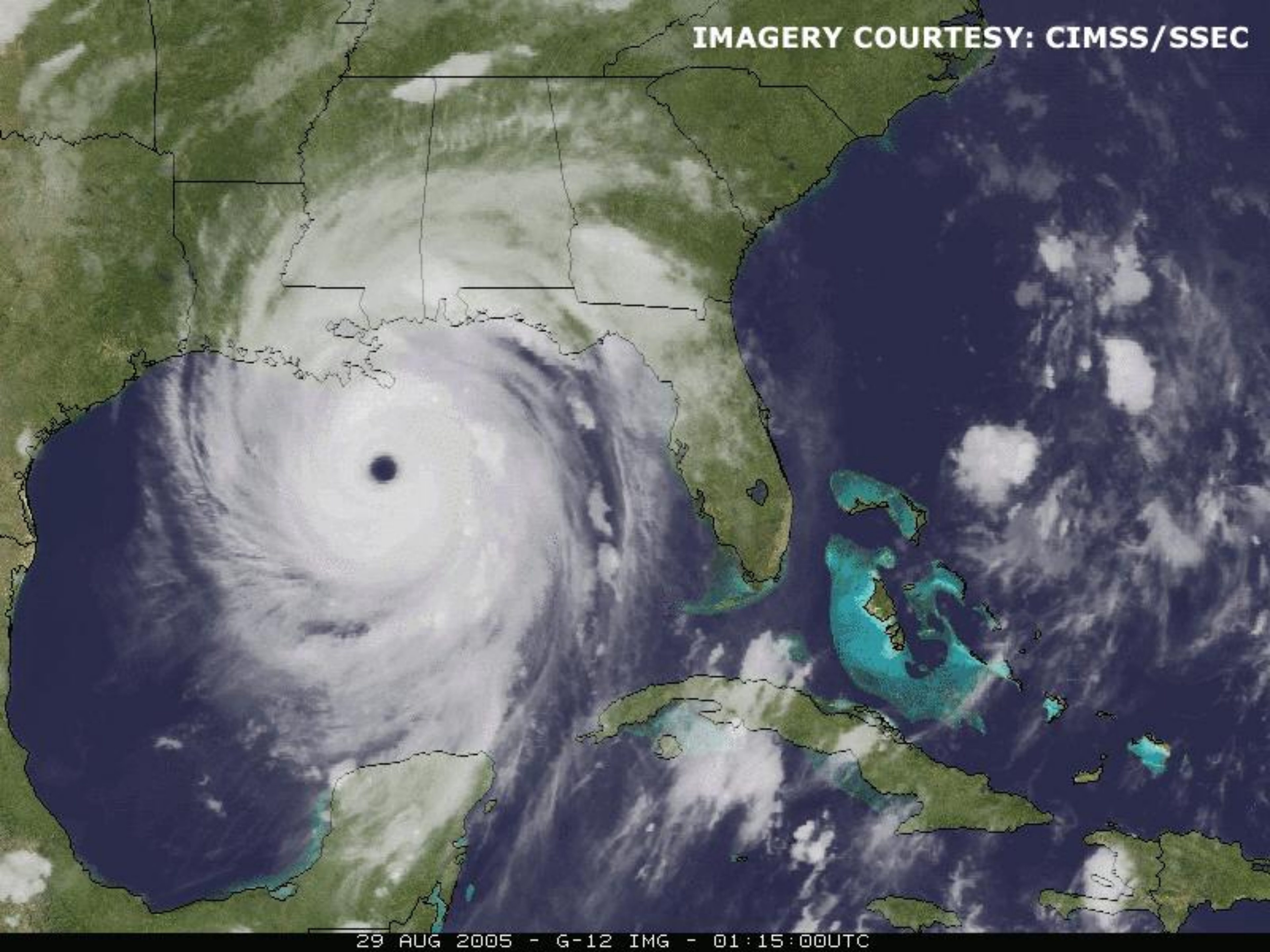
90
GOES-12 INFRARED 00:45UTC 29 AUG 05 UW-CIMSS McIDAS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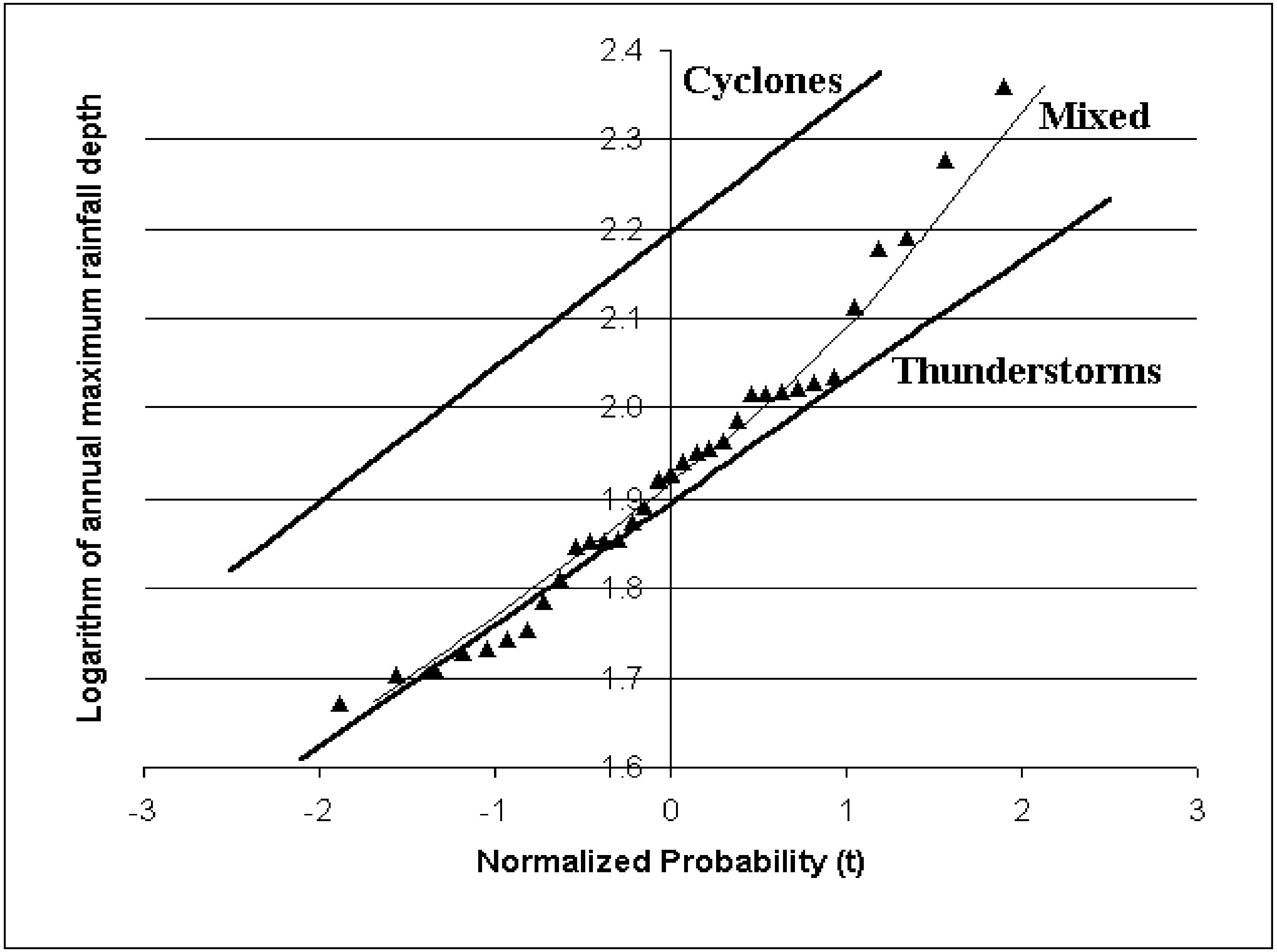
29 AUG 2005 - G-12 IMG - 01:15:00UTC

Mixed distribution of combined cyclonic storms and thunderstorms



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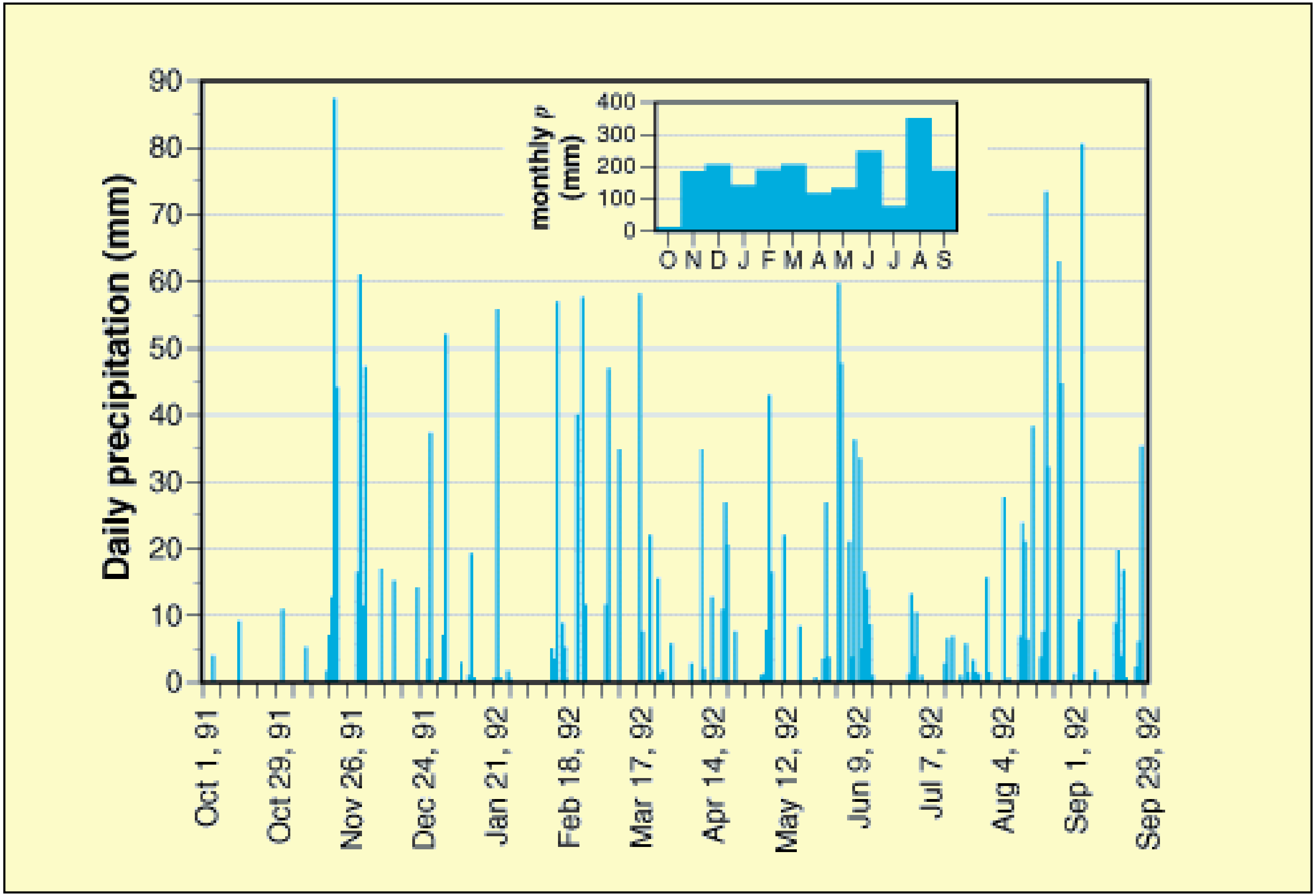
Precipitation Parameters

- Amount of precipitation – units of depth (e.g. l/m_2 = mm)
- The duration of event or period – units of time (e.g. min, hour, day, month, year etc.)
- Intensity = amount/duration (e.g. mm h^{-1})
  - May be for all or only part of the total duration of the storm
    - seconds, minutes, hours, days, years, ...
  - Long durations have usually greater amounts
  - Shorter durations have usually greater intensities
- Graph of precipitation vs. time is a <u>hyetograph</u>
- Seasonal distributions, depending on atmospheric circulation patterns

Temporal distribution (1/2)



(Hornberger et al., 1998)

Temporal distribution (2/2)

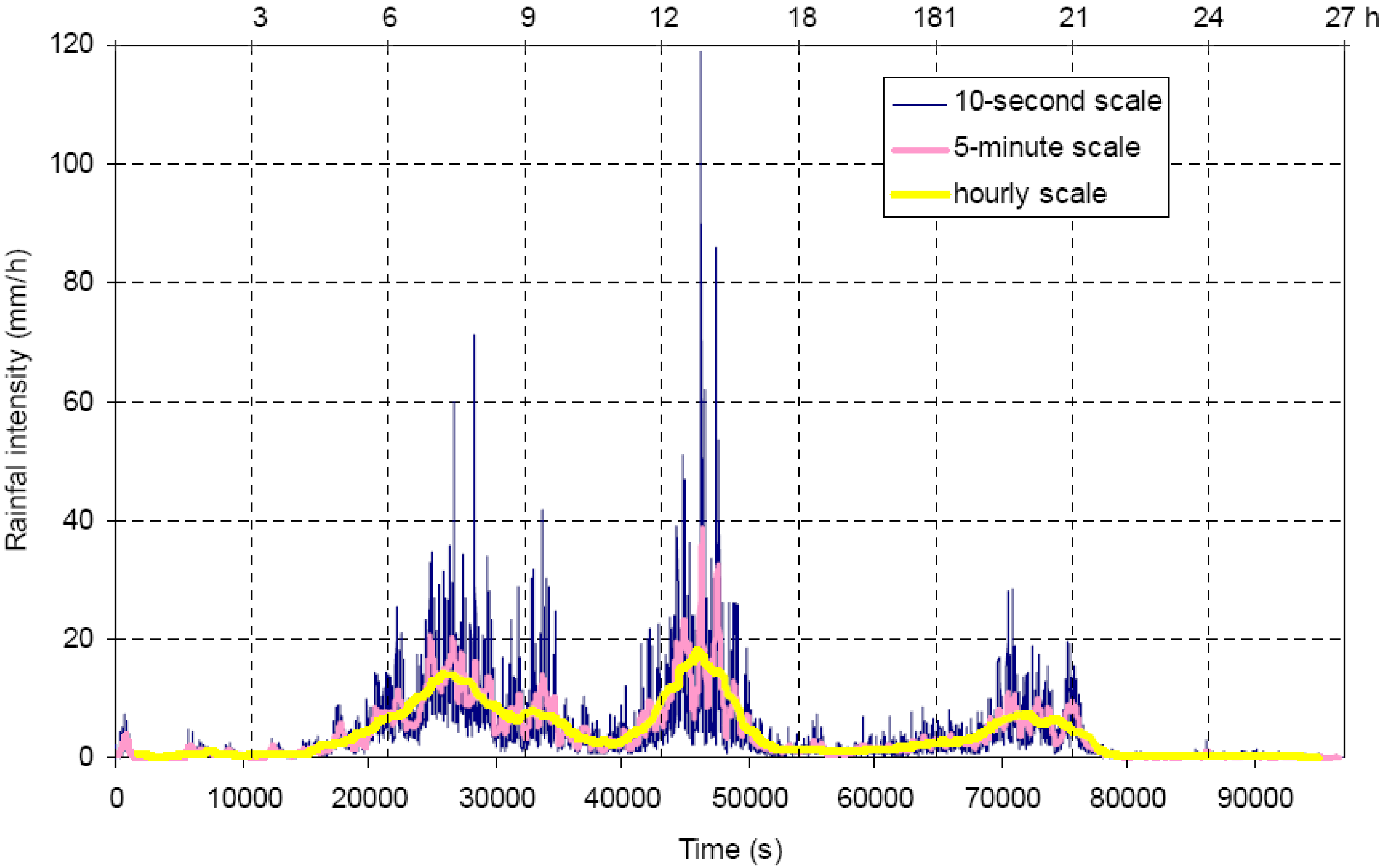
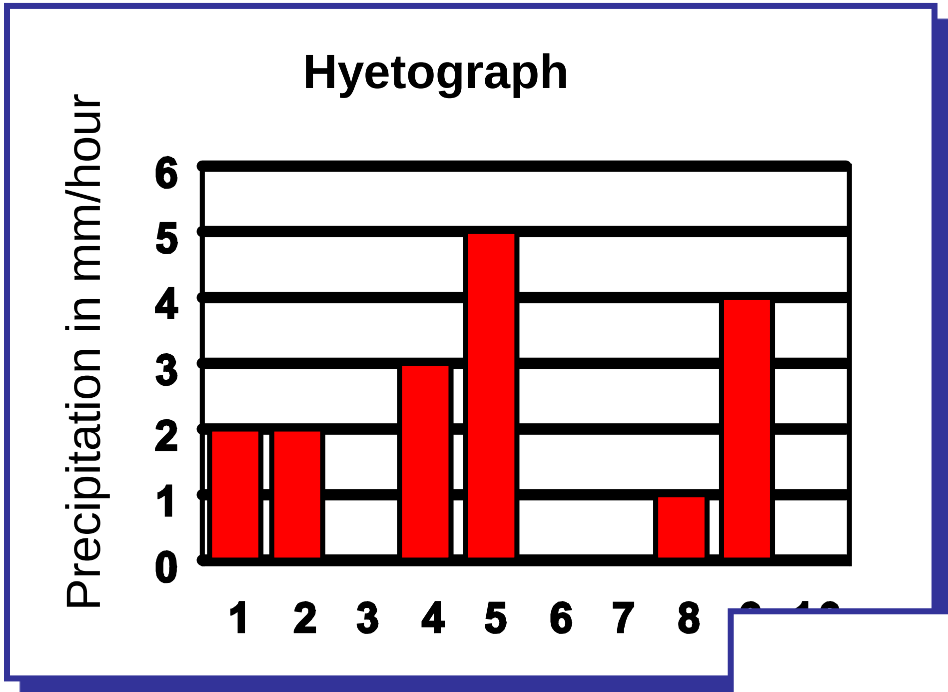
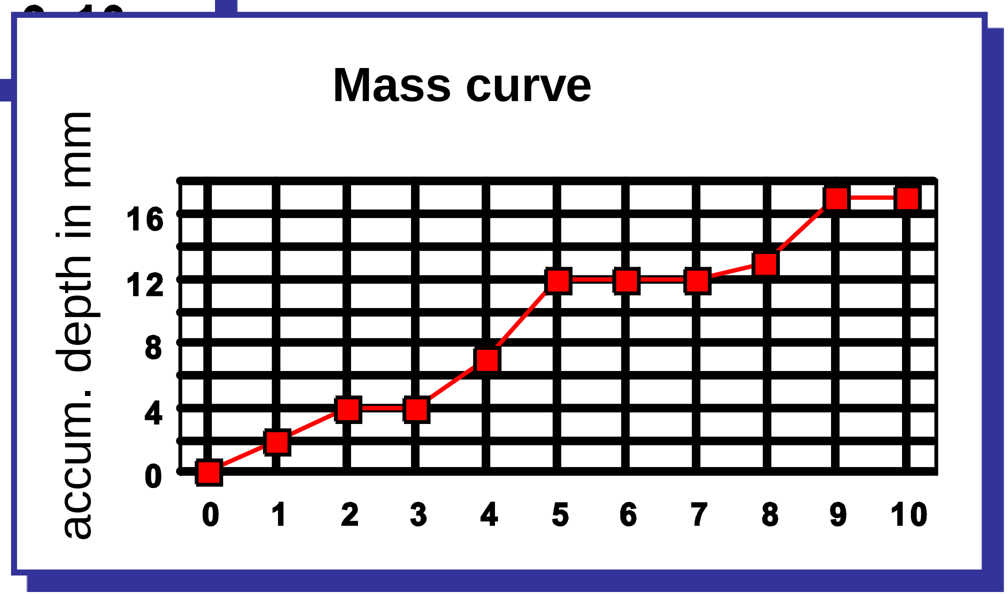


Fig. 8 Time series of a storm in Iowa, USA measured at the University of Iowa with temporal resolution of 10 seconds (Georgakakos et al., 1994); time zero corresponds to 1990-02-12T17:03:39.

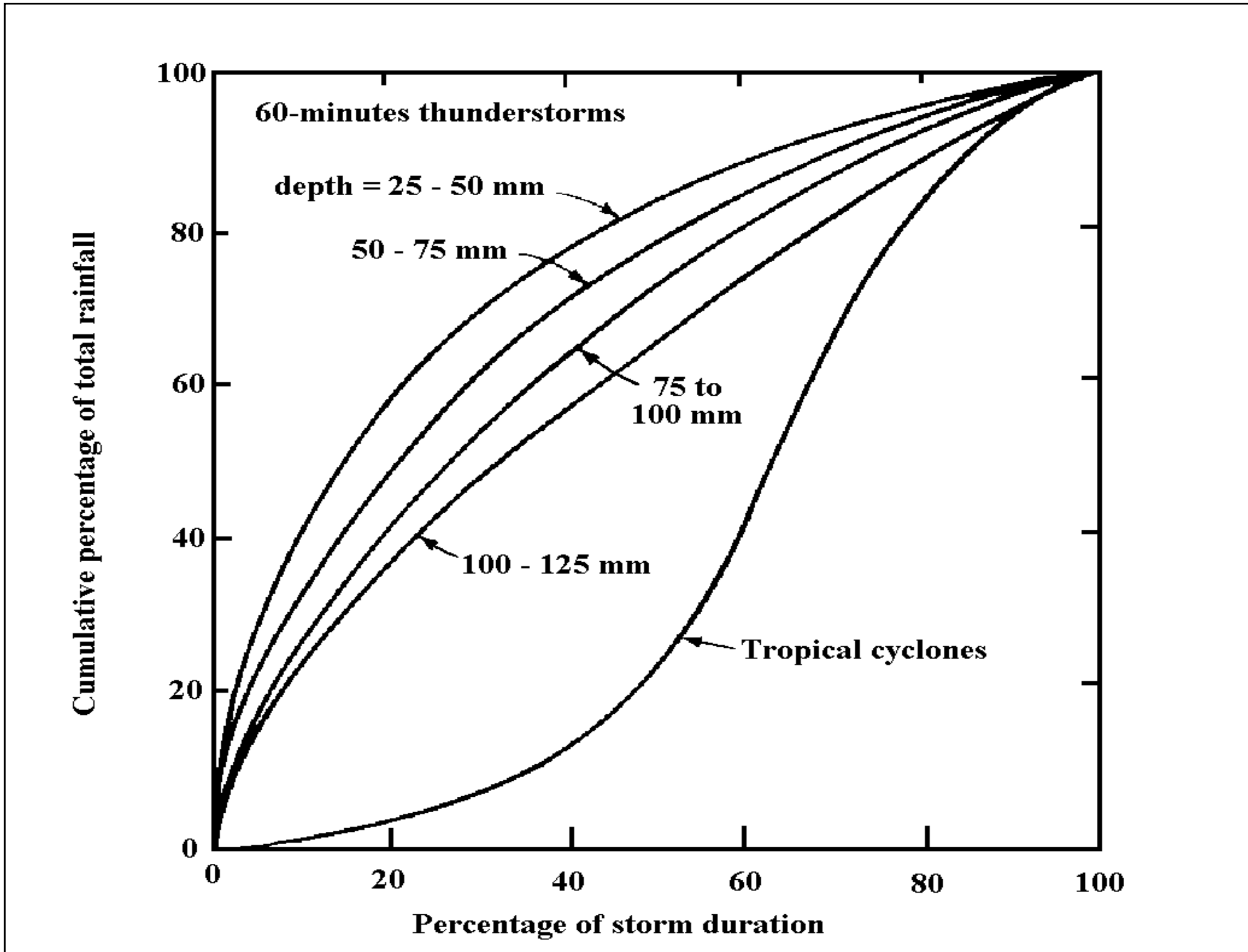
(Koutsoyiannis and Langousis, 2009)

Rainfall data





Rainfall-intensity distribution



Typical percentage mass curves of rainfall for

Frequency analysis

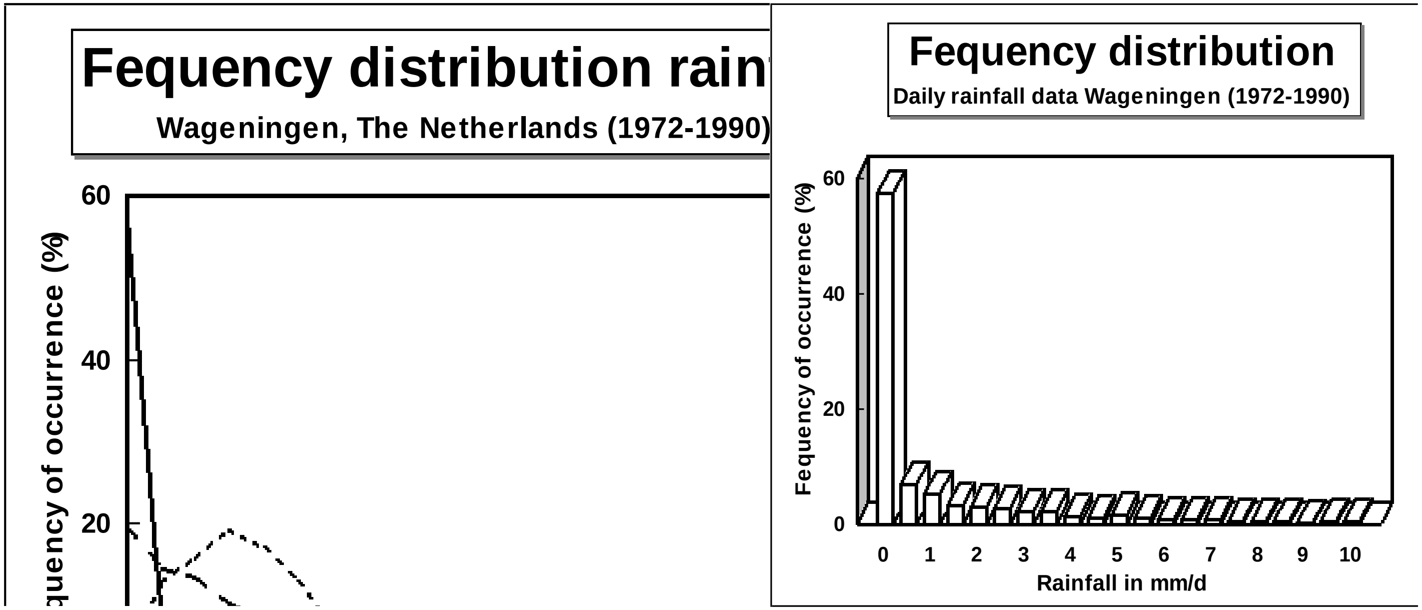
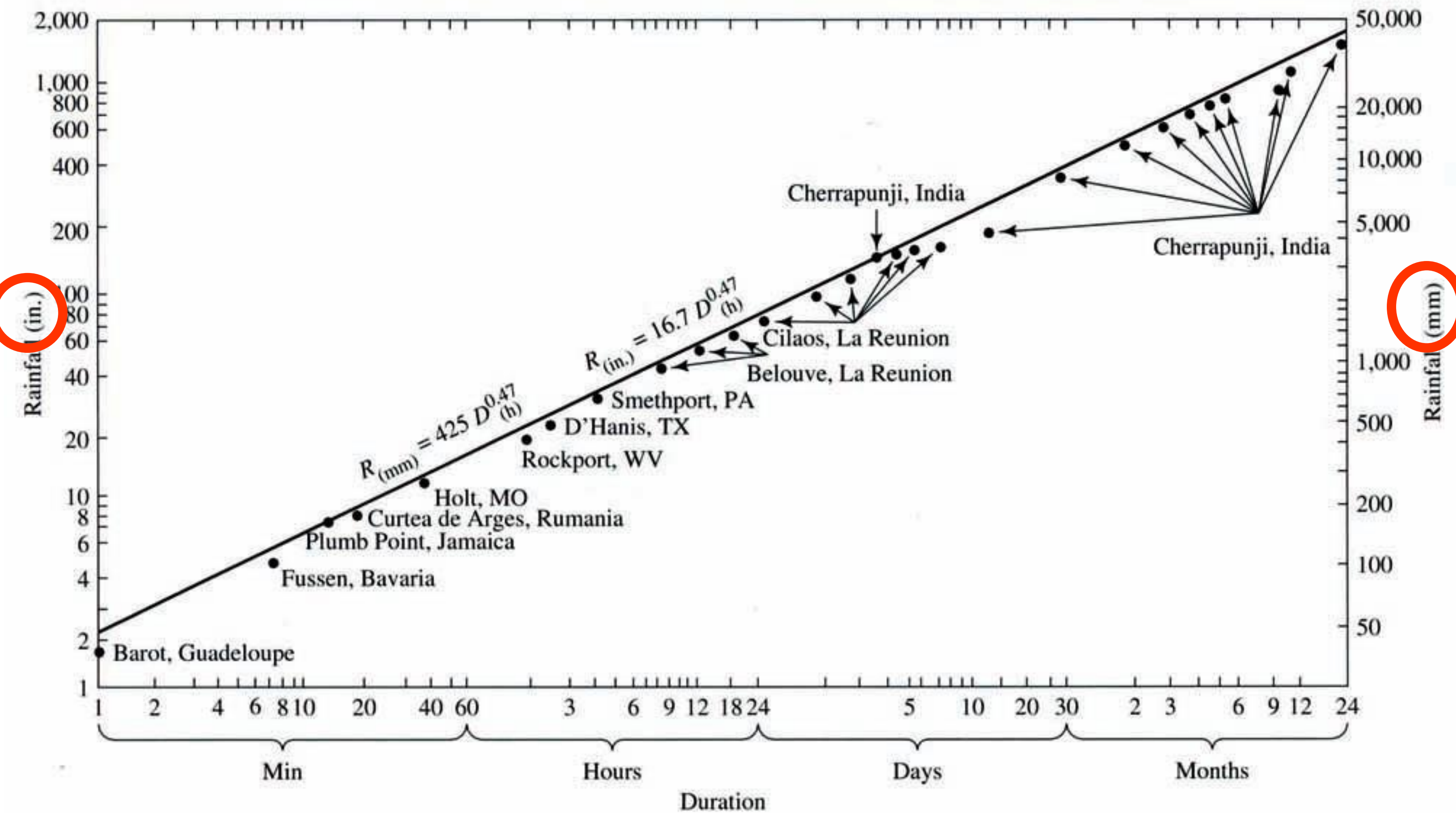


Figure .16 Frequency distribution of 1, 10 and 30 day rainfall (a); hystogram of daily rainfall (b)

k \ #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	2	8	0	0	0	0	0	12	3	8	24	2	0
2		0	2	10	8	0	0	0	0	12	15	11	32	26	2
5					10	10	10	8	0	12	15	23	47	49	37
10										22	25	33	55	49	49

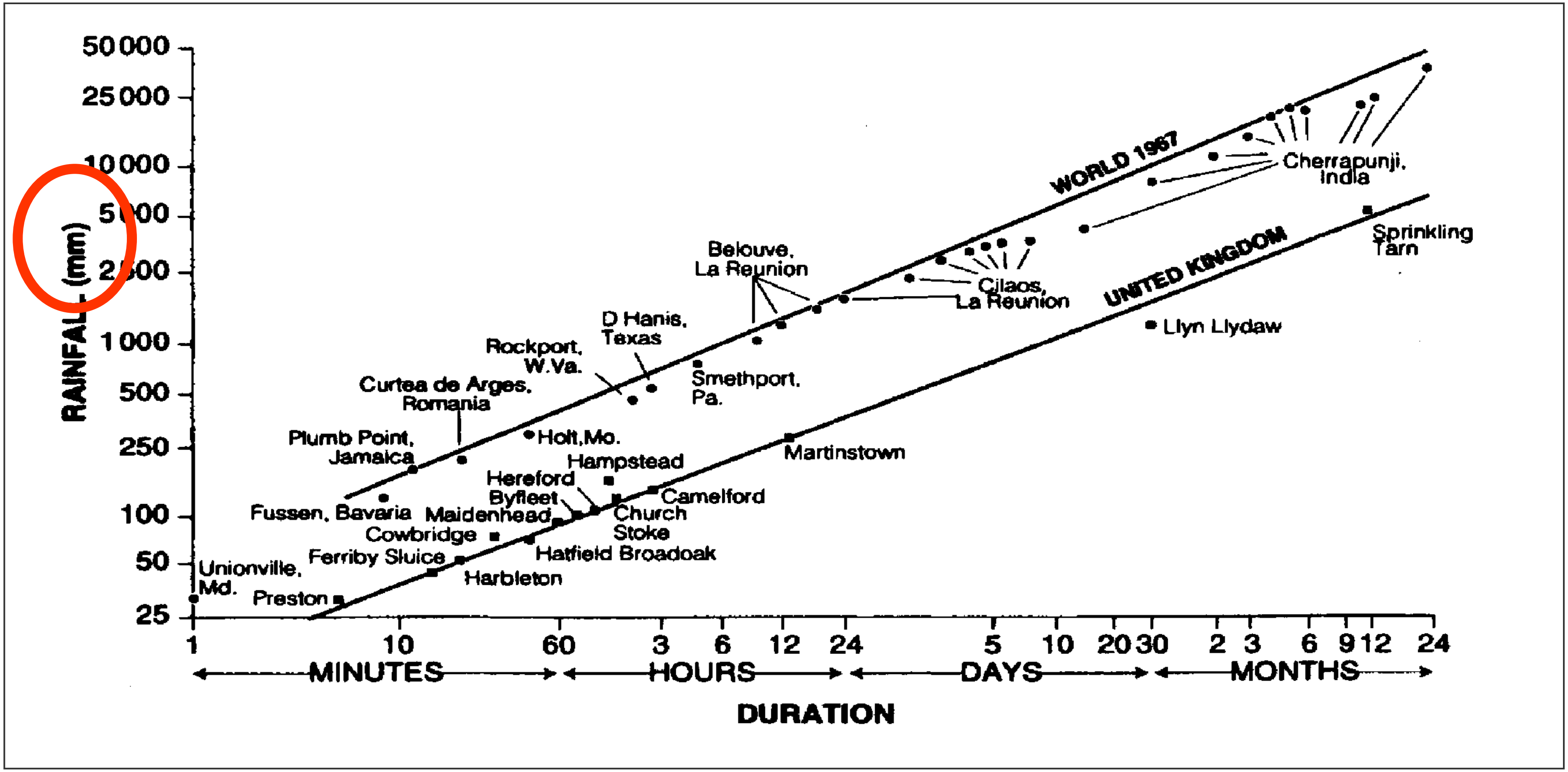
Observed extreme precipitation data around the world



(Dingman, 2001)

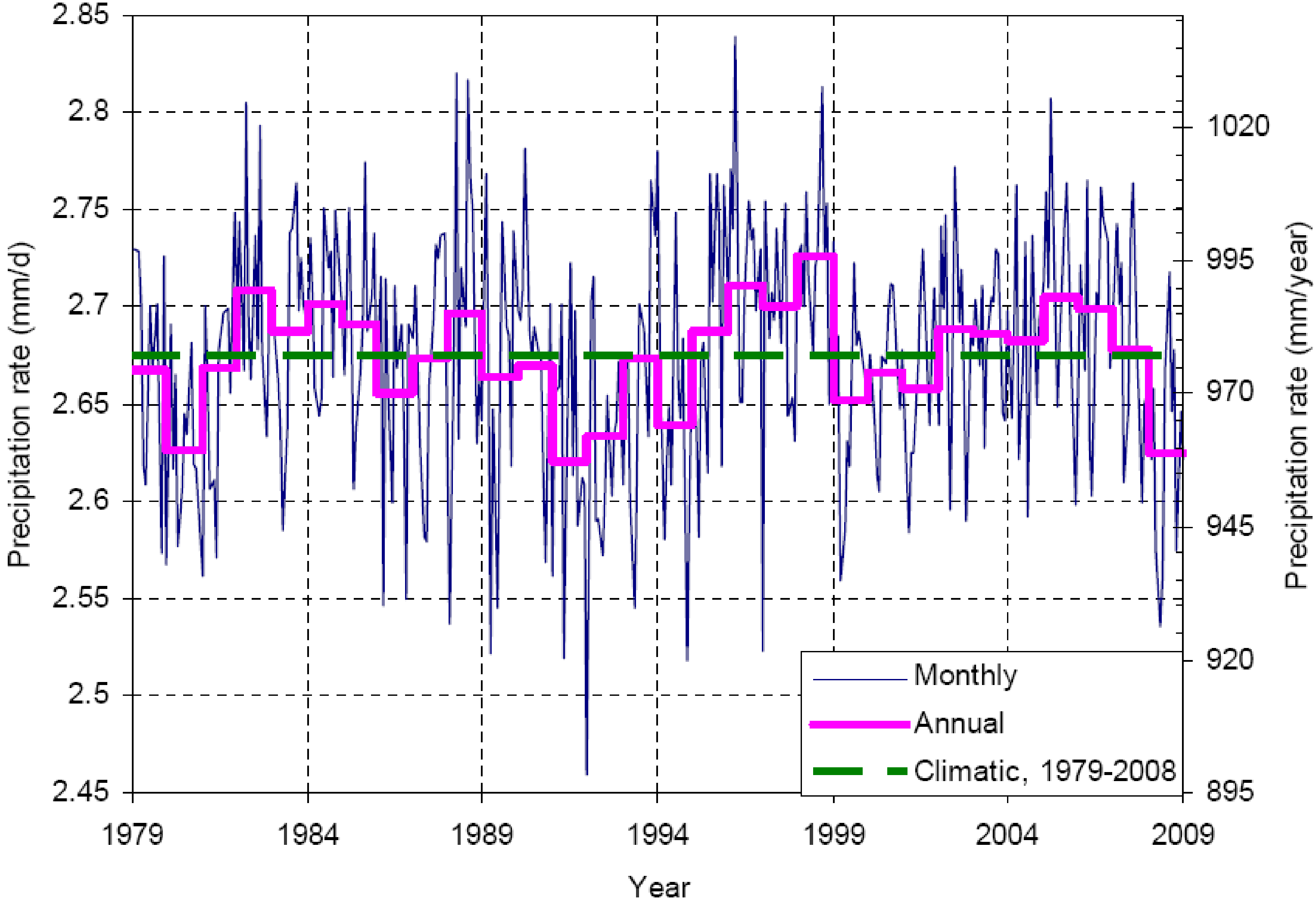
Annual average in Cherrapunji (India) about 10,420 mm/a !!

Observed extreme precipitation data
World vs. United Kingdom



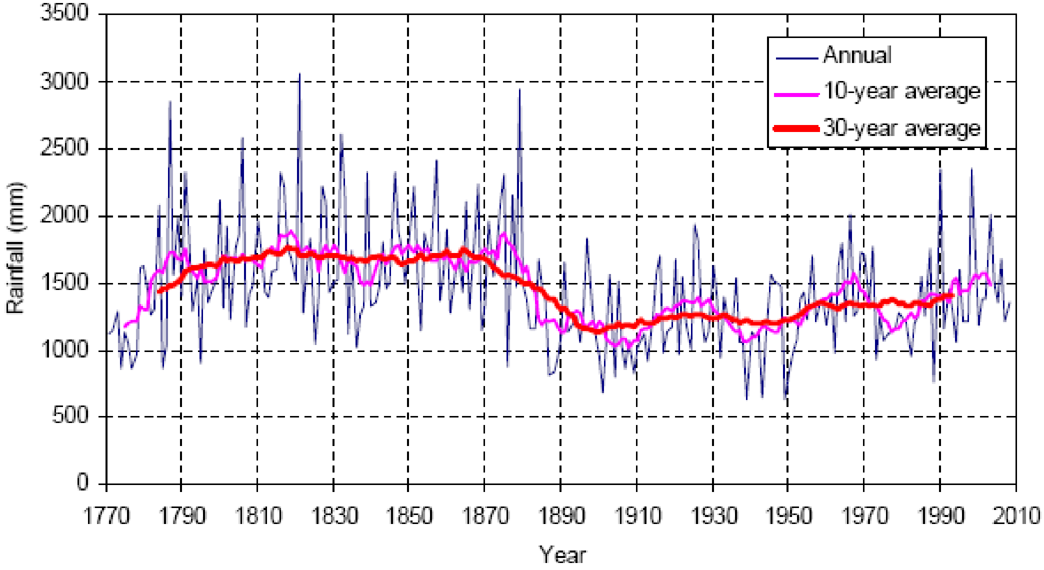
Magnitude-duration relationship for the world and the UK extreme rainfalls (source: Ward & Robinson, 1990).

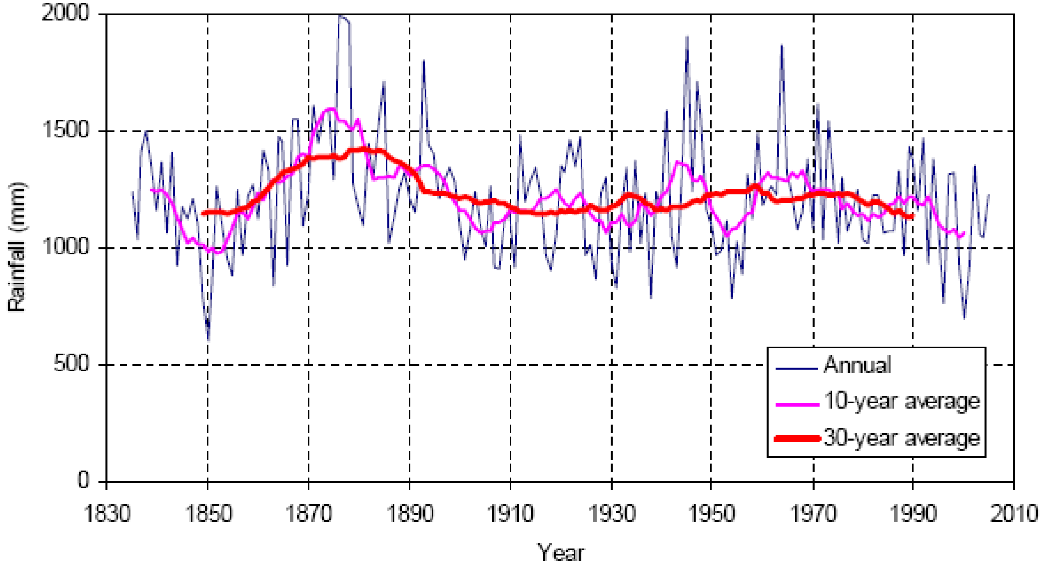
Evolution of global precipitation based on averaged monthly data from GPCP for 1979-2008



(Koutsoyiannis and Langousis, 2009)

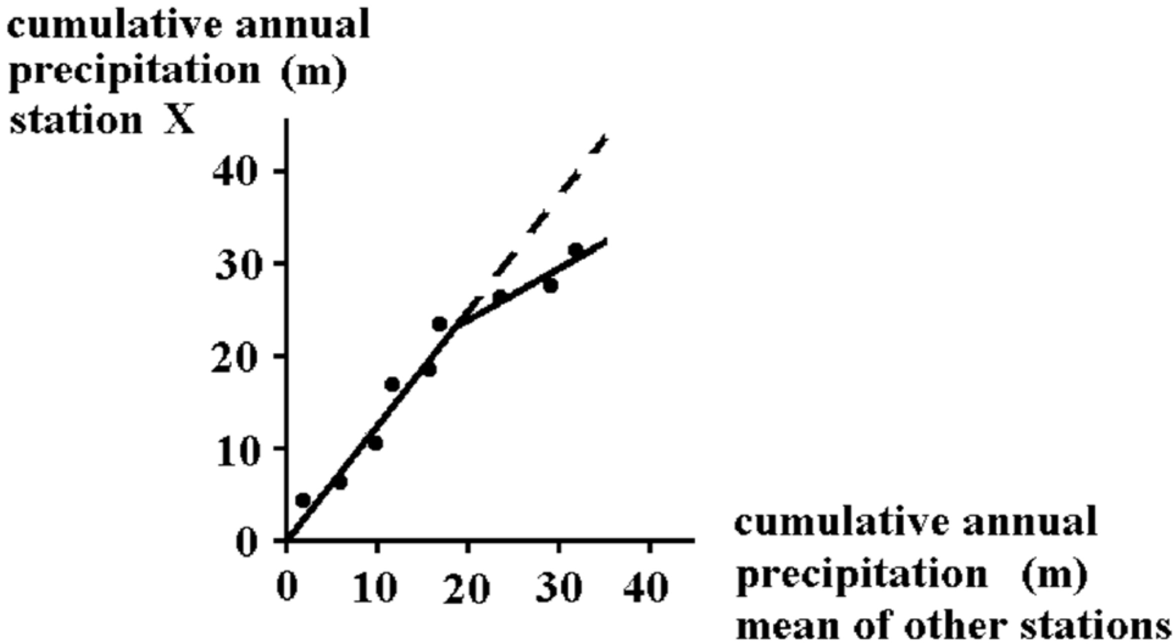
Annual precipitation time series of two stations with the longest records worldwide: Seoul, Korea (upper); Charleston City, USA (lower) (data source: KNMI; climexp.knmi.nl)





(Koutsoyiannis and Langousis, 2009)

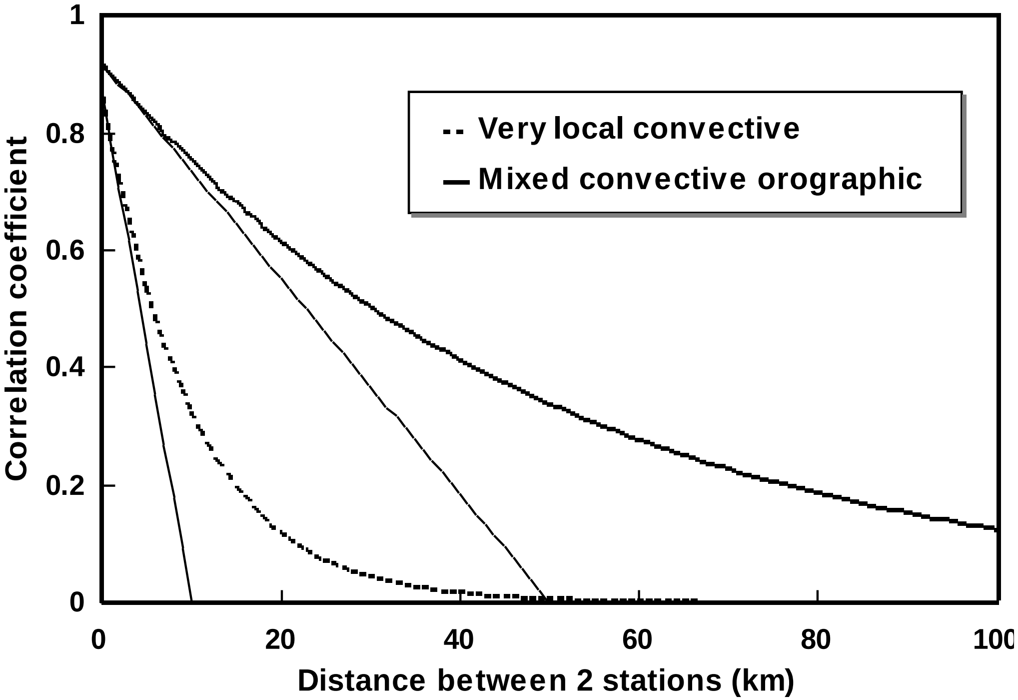
Rainfall data screening



Spatial homogeneity:

$$P_{est} = \frac{\sum \left(P/r^b \right)_i}{\sum \left(1/r^b \right)_i}$$

Correlation between rainfall stations



Kagan's formula:

$$\rho(r) = \rho_0 \, e^{-\frac{r}{r_0}}$$

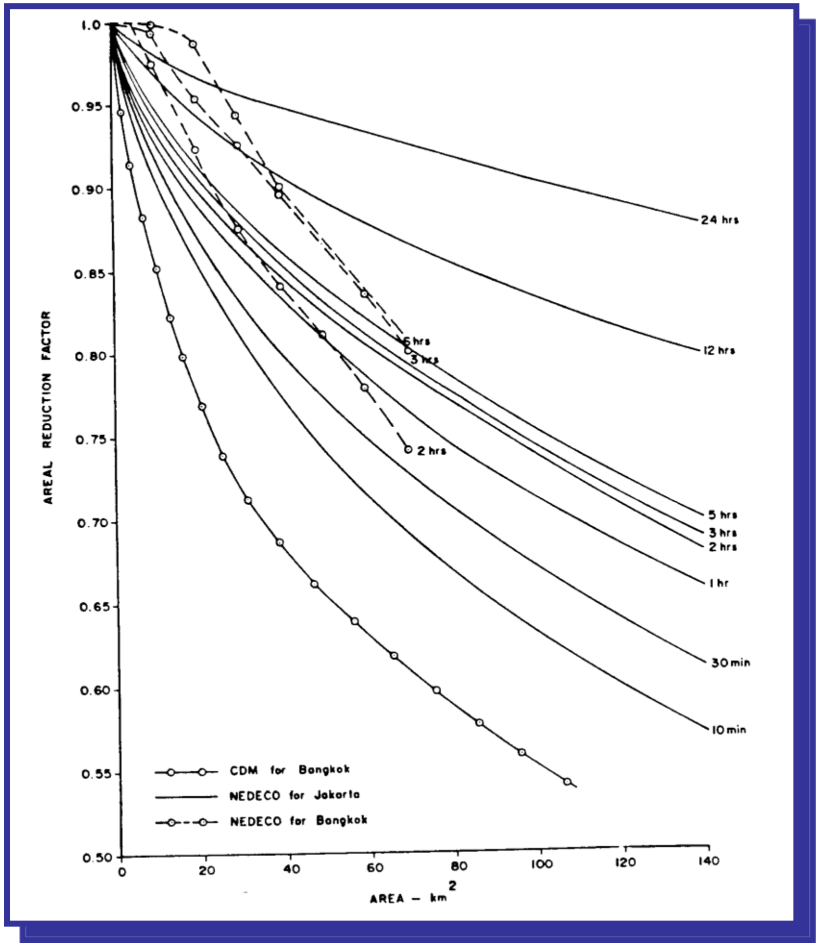
Rain type	Period 1 hour		Period 1 day		Period 1 month	
	r_o (km)	p_o	r_o (km)	p_o	r_o (km)	p_o
Very local convective	5	0.80	10	0.88	50	0.95
Mixed convective orographic	20	0.85	50	0.92	1500	0.98
Frontal rains from depressions	100	0.95	1000	0.98	5000	0.99

Areal Reduction Factor

$$ARF = P_a/P_p$$

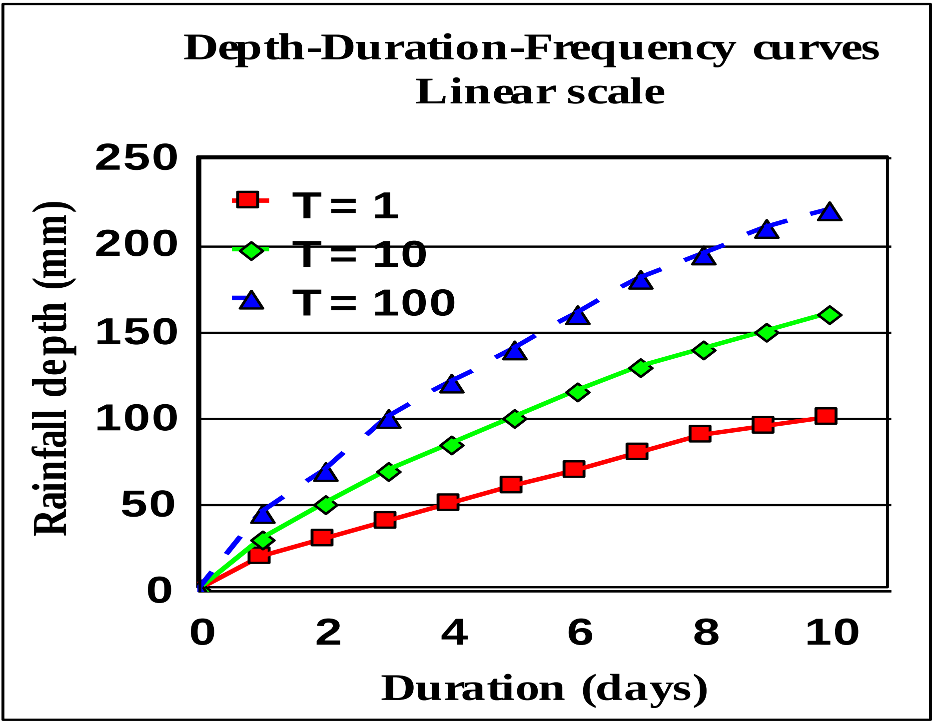
ARF is a function of:

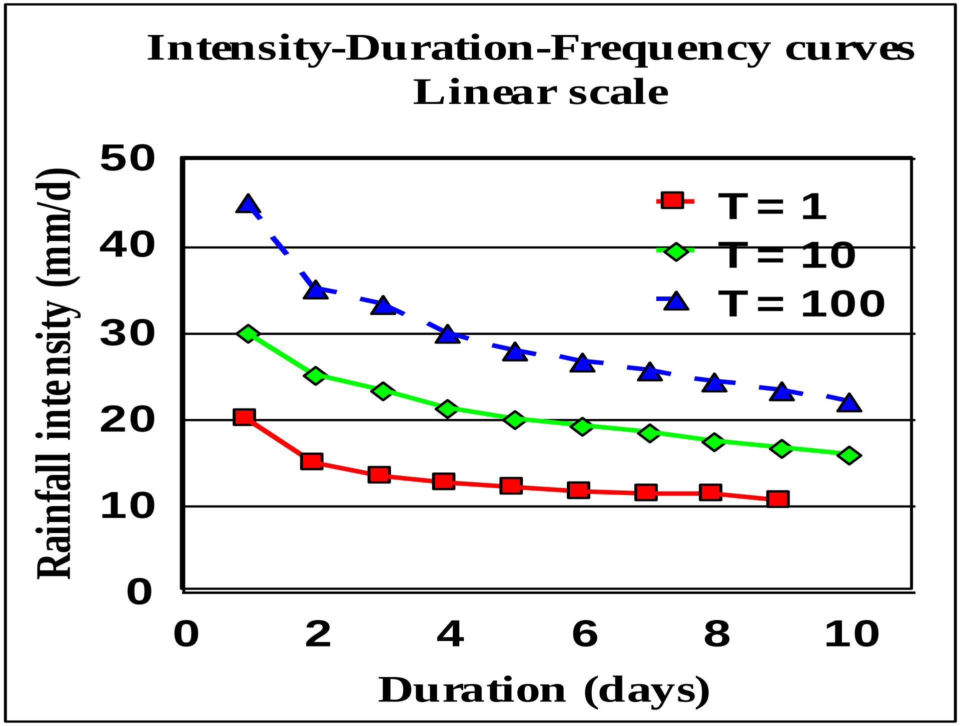
- rainfall depth
- storm duration
- storm type
- catchment size
- return period



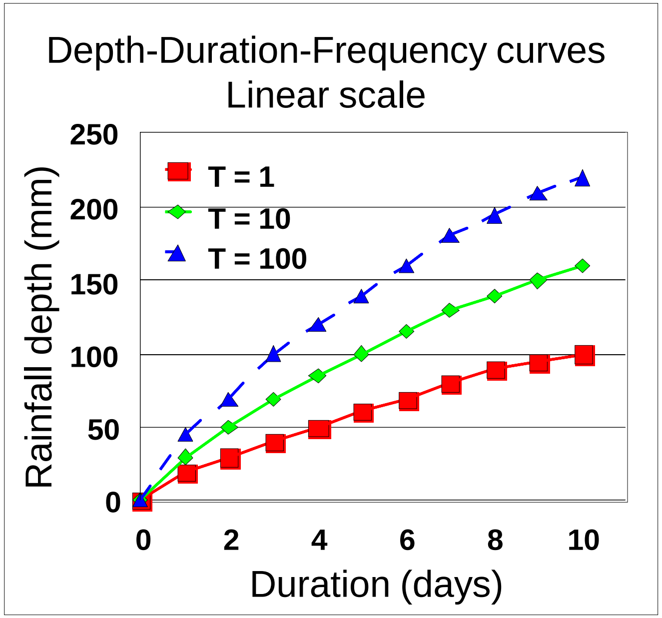
DDF
Depth-Duration-Frequency curves

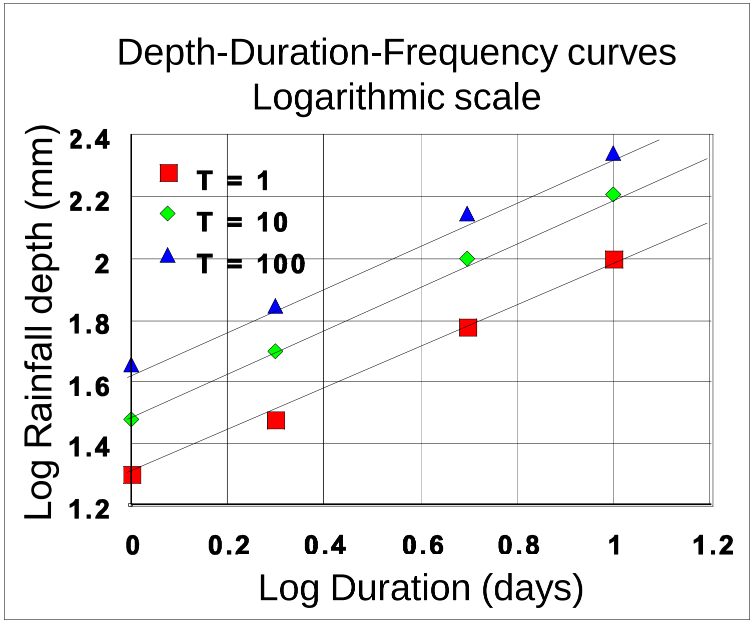
IDF
Intensity-Duration-Frequency curves

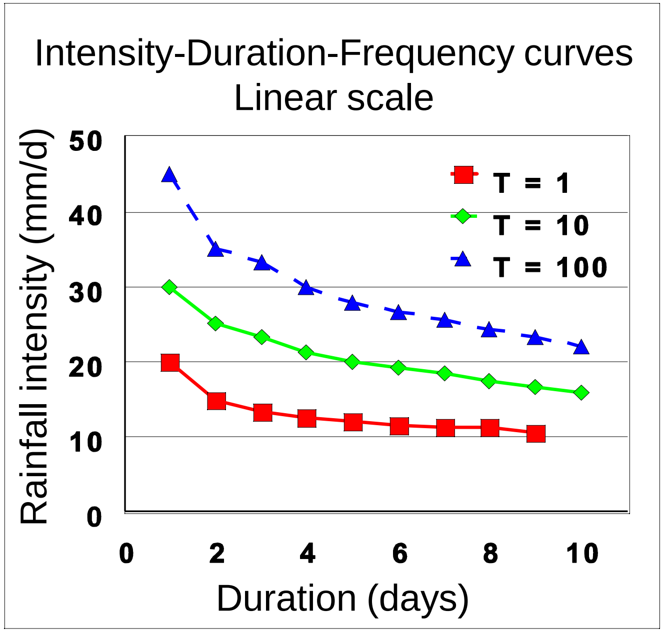


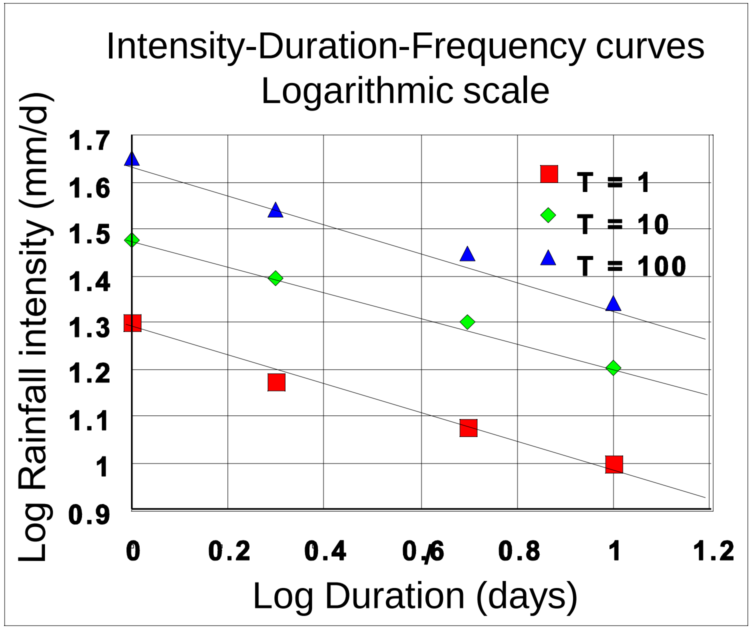


Frequency analysis









Data screening

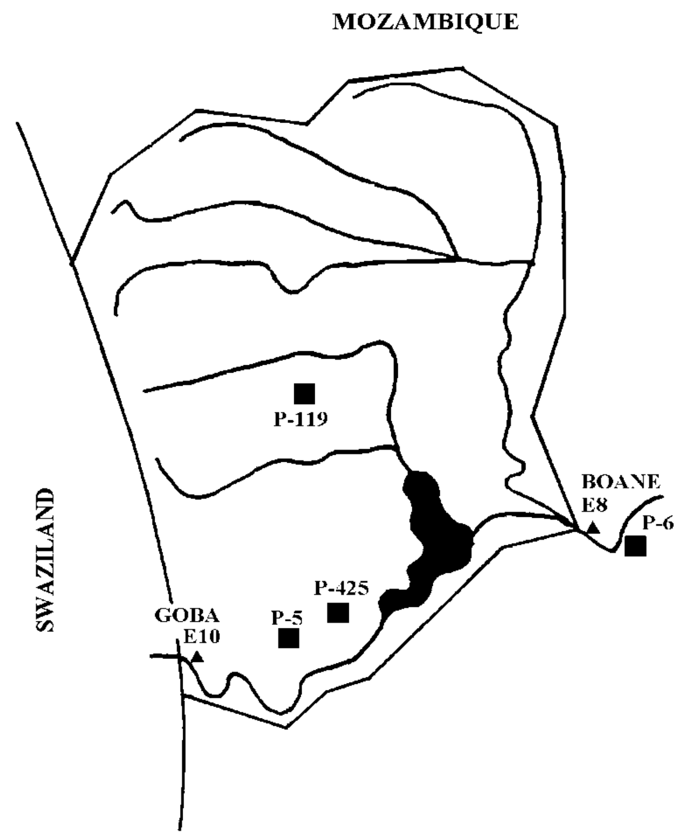
Never assume that meteorological data are of consistent good quality!

1. **Tabular comparison**
2. **Time series plotting (visual inspection)**
3. **Spatial homogeneity test**
4. **Double mass analysis**

See workshop

APRIL	P425	P119	P5	P6
58/59	3.1	8.5	12.4	16.0
59/60	124.1	179.8	145.7	102.6
60/61	55.7	47.4	65.0	116.6
61/62	63.5	81.6	72.6	59.2
62/63	60.5	31.3	54.5	61.1
63/64	60.0	96.9	47.2	25.4
64/65	25.0	33.6	31.0	42.0
65/66	16.4	15.3	8.5	30.9
66/67	132.2	114.4	130.6	78.2
67/68	16.9	32.6	83.3	24.3
68/69	161.7	110.0	99.4	143.7
69/70	10.2	9.5	14.8	9.0
70/71	91.0	95.9	94.0	86.6
71/72	34.1	74.5	35.6	24.9
72/73	48.5	98.0	59.2	53.9
73/74	40.3	115.3	104.0	48.4
74/75	62.2	107.4	61.0	126.3
75/76	63.7	76.1	57.0	57.9
76/77	10.2	22.6	37.5	18.9
AVG	56.8	71.1	63.9	59.3
STD	42.8	45.2	37.4	38.9
MIN	3.1	8.5	8.5	9.0
MAX	161.7	179.8	145.7	143.7

Example of tabular comparison of monthly rainfall values of 4 stations (P5, P6, P119 and P425) in the Ubeluzi catchment in Mozambique



Double mass analysis

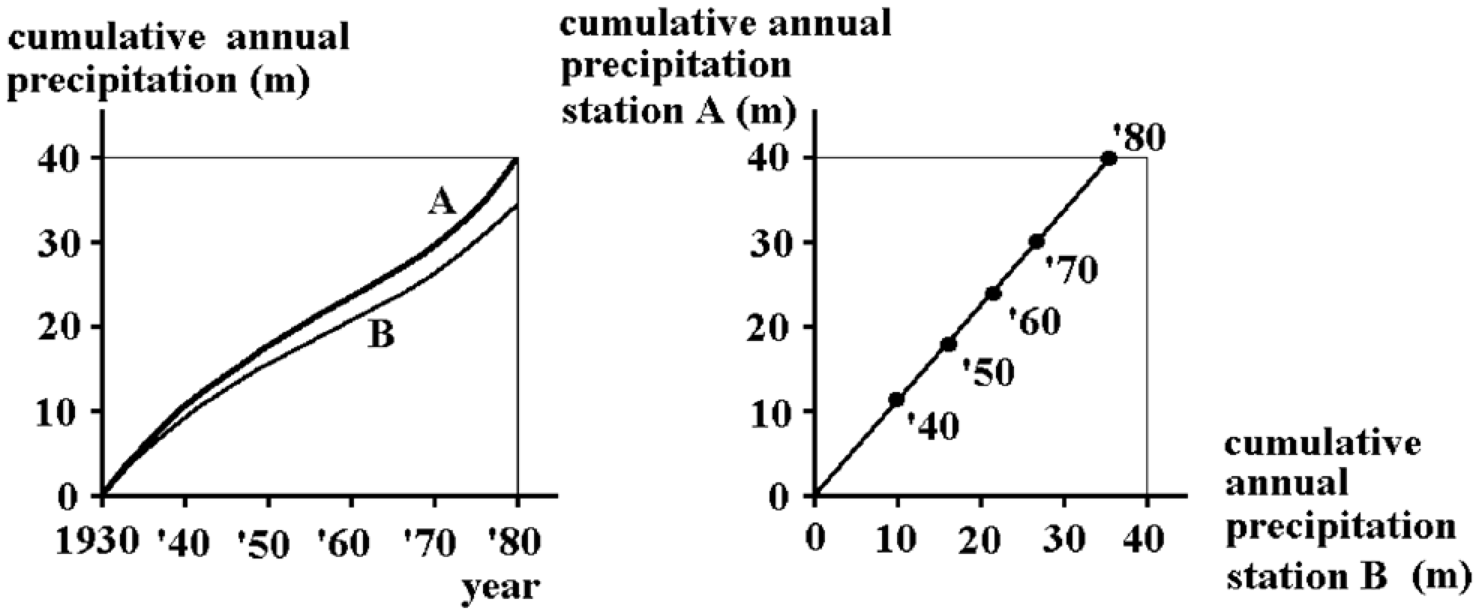
For monthly rainfall data (January) 1951 - 1982

Stations P425 vs. the mean of P5, P6 and P119

January	P425	P119	P5	P6	P425 sum	Average P119,P5,P6
					0	0
51/52	*84.5*	108.8	114.2	70.8	84.5	97.9
52/53	*162.6*	305.4	186.2	172.3	247.1	319.2
53/54	*62.9*	84.2	87.4	44.3	310.0	391.2
54/55	*164.2*	293.8	154.1	235.0	474.2	618.8
55/56	*68.6*	123.0	85.6	54.9	542.8	706.7
56/57	*57.9*	87.4	66.2	59.8	600.7	777.8
57/58	*171.1*	253.1	216.2	171.7	771.8	991.5
58/59	175.3	123.7	162.9	79.5	947.1	1113.5
59/60	79.5	63.5	76.4	84.3	1026.6	1188.2
60/61	56.0	49.1	110.0	84.5	1082.6	1269.4
61/62	142.4	118.1	93.1	188.6	1225.0	1402.7
62/63	95.7	115.8	111.8	84.7	1320.7	1506.8
63/64	249.0	173.2	210.3	215.5	1569.7	1706.5
64/65	12.3	56.2	14.3	40.4	1582.0	1743.4
65/66	546.8	672.2	625.1	587.6	2128.8	2371.7
66/67	76.6	190.1	48.5	162.1	2205.4	2505.3
67/68	121.5	113.7	92.0	71.4	2326.9	2597.7
68/69	157.7	188.7	125.5	111.4	2484.6	2739.5
69/70	4.7	13.0	98.4	9.6	2489.3	2779.9
70/71	51.8	98.6	87.9	53.1	2541.1	2859.7
71/72	218.0	320.6	156.8	210.4	2759.1	3089.0
72/73	56.7	57.2	79.1	63.3	2815.8	3155.5
73/74	108.6	209.6	151.7	299.5	2924.4	3375.8
74/75	81.3	183.8	138.7	232.3	3005.7	3560.7
75/76	210.2	416.7	311.4	275.0	3215.9	3895.1
76/77	44.3	150.9	77.0	115.5	3260.2	4009.6
77/78	122.0	354.0	305.6	202.9	3382.2	4297.1
78/79	122.5	171.2	60.5	129.0	3504.7	4417.3
79/80	62.2	157.7	52.9	33.8	3566.9	4498.8
80/81	*160.0*	112.5	*183.2*	194.4	3726.9	4662.1
81/82	*29.2*	96.1	*31.7*	24.5	3756.2	4712.9

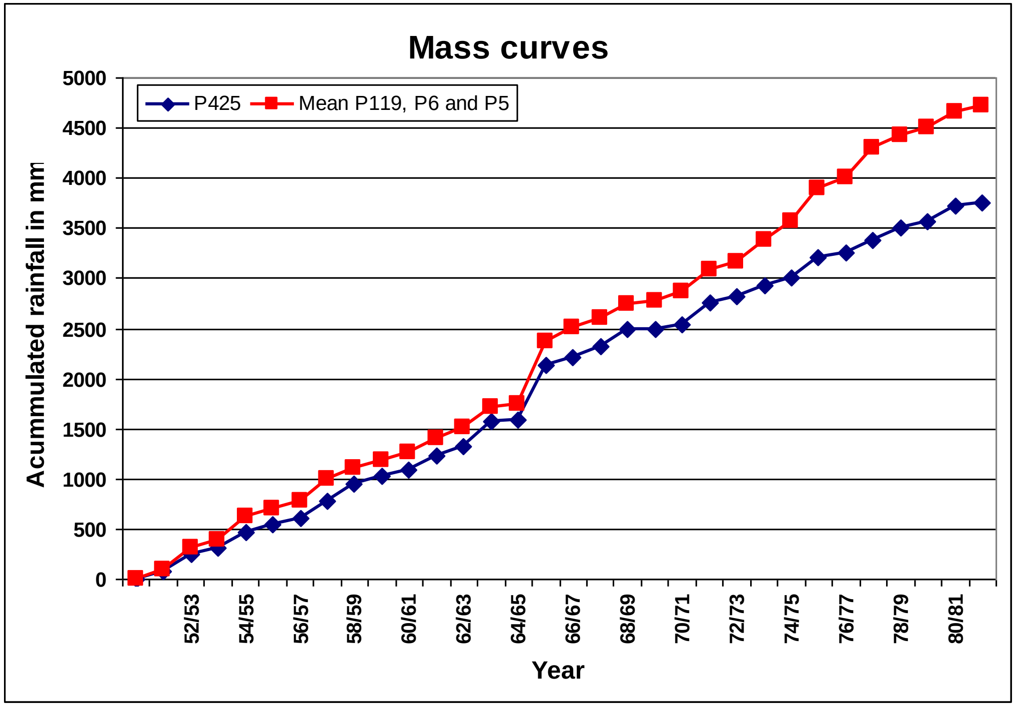
Rainfall data screening

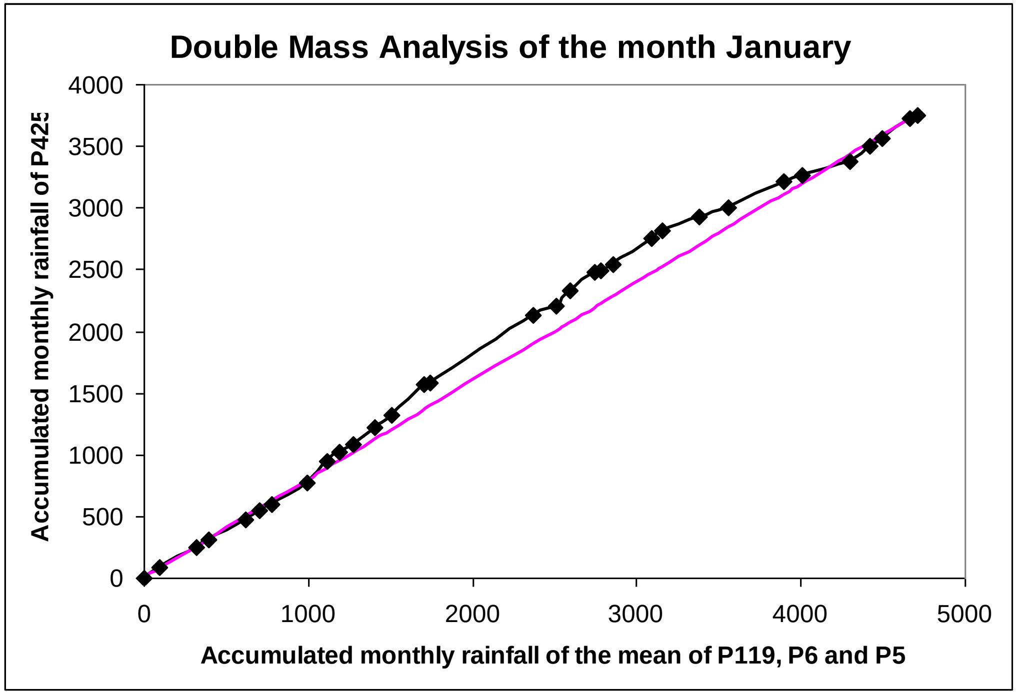
Double mass curve:

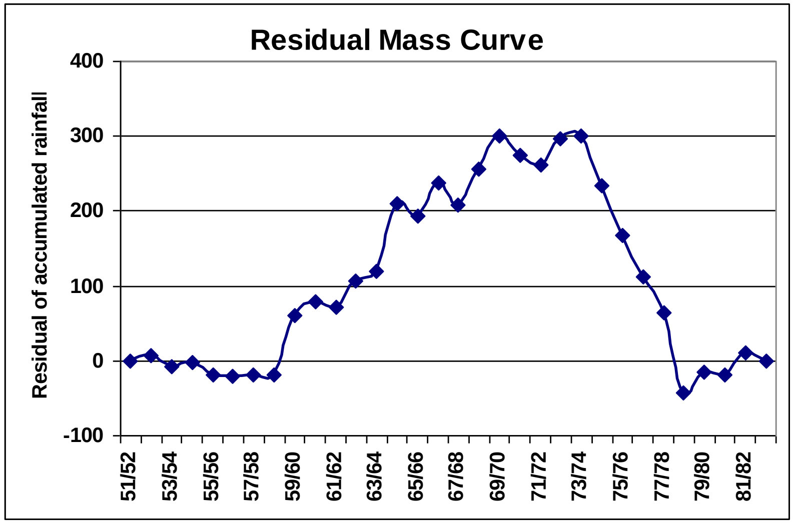


Data Screening

Double mass analysis







Objectives of this Lecture

- Types of precipitation
- Precipitation formation processes
- Precipitation parameters
- Measurement techniques for precipitation
- Areal estimation of precipitation

Classical rain gauge according to Hellmann

usually read daily at 7 AM

Precipitation Measurement
The Principal

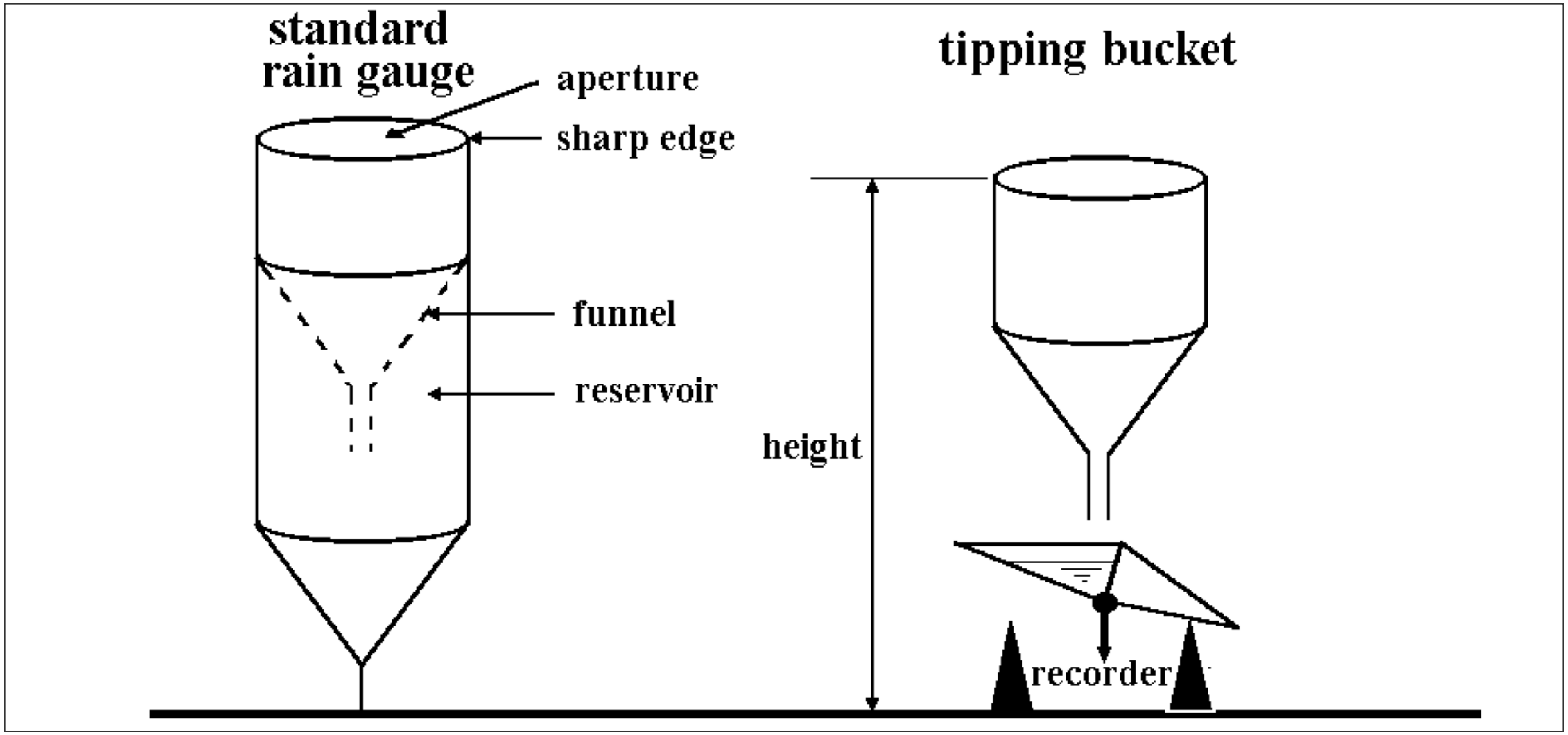


Fig. 2.4 Rain gauges

Annual totalisator

Read once in a year, or once per season

Annual totalisator for high mountain areas

There are also simple rain gauges that cost less than US$ 5!!

(and empting makes fun!)

There are also simple rain gauges that cost less than US$ 2!!

(and empting makes fun!)

Precipitation Intensity Measurement

Pluviograph

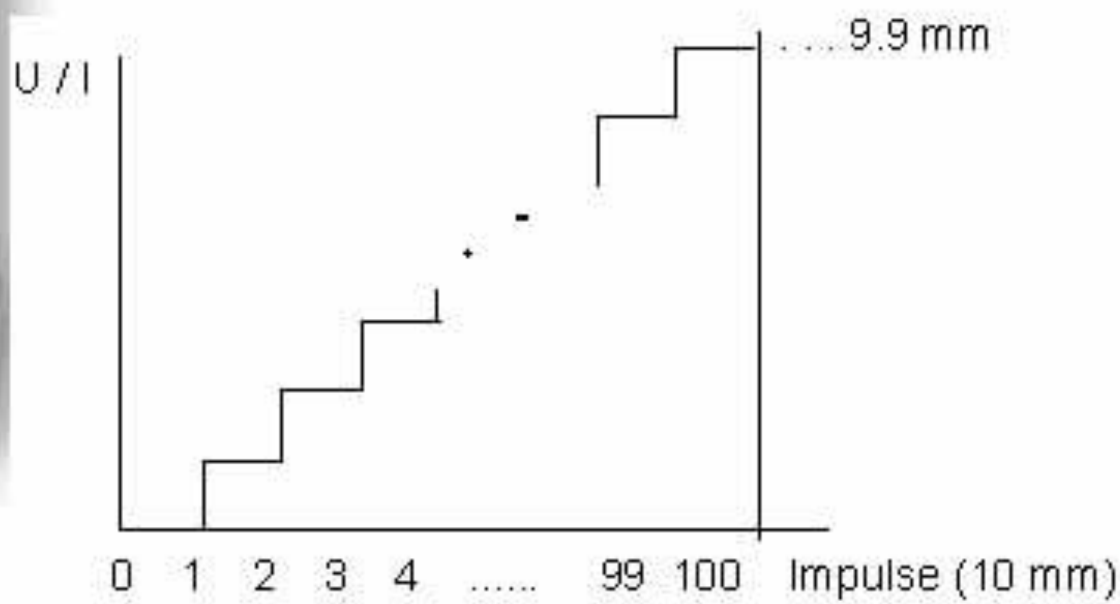
Rainfall intensity gauge

- Different types
  1. Swimmer (see picture)
  2. Tipping bucket
  3. Weighing device
  4. Droplet counter

Tipping bucket

System Joss-Tognini

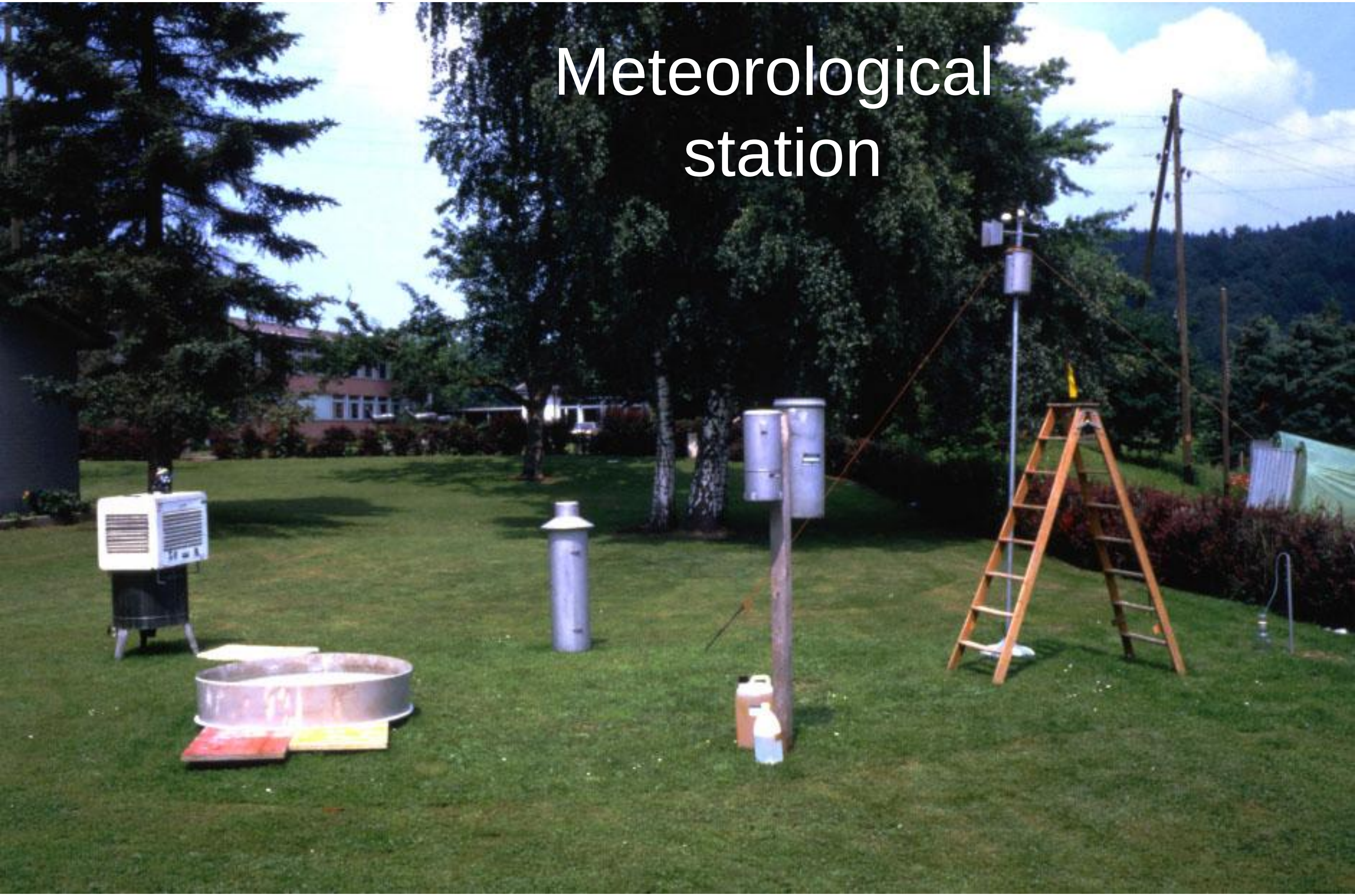
Tipping bucket



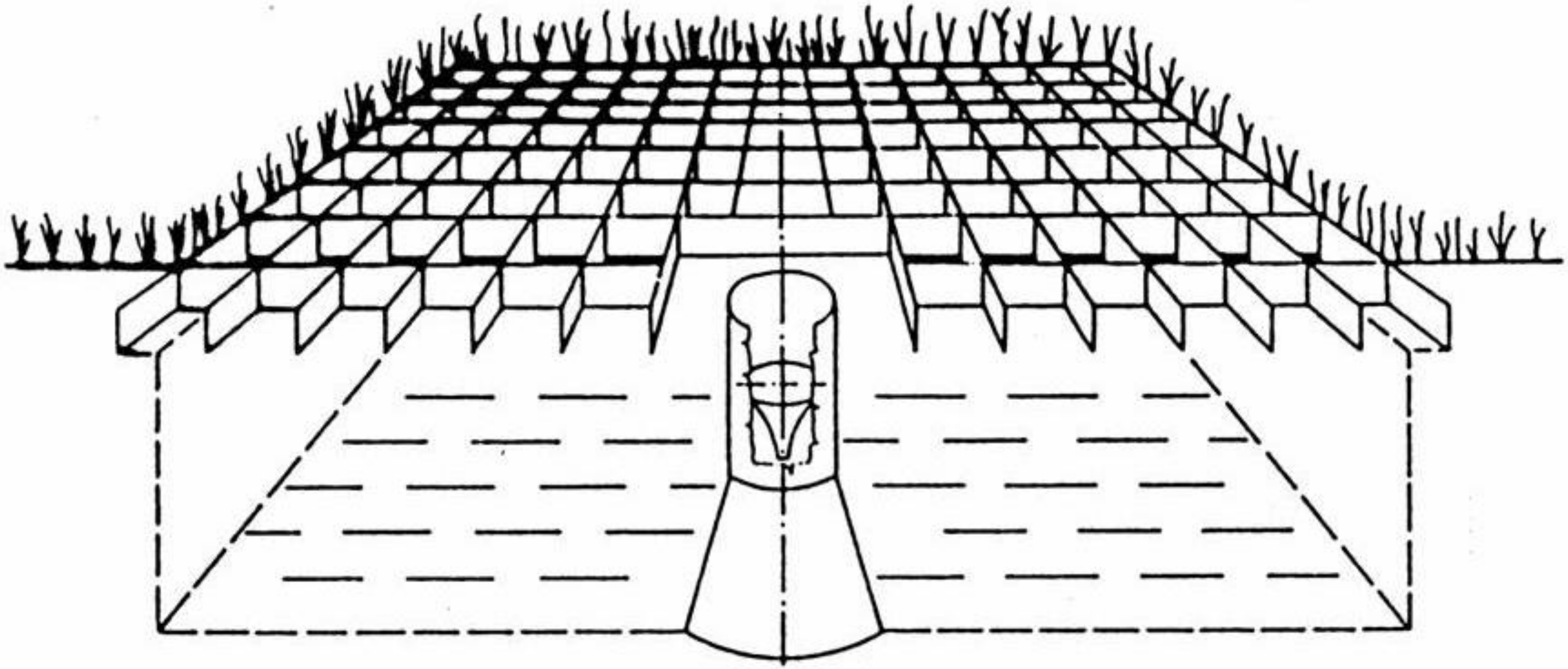
Quelle: http://www.thiesclima.com/nieders.htm

Tipping Bucket Gauge

Meteorological station



Measurement of the ‚real' precipitation on the ground



Systematic errors during rainfall measurements

- Deformation of the wind array above the gauge (rain about 2-5 (up to 10) %; snow 10-40 (or even more!) %)

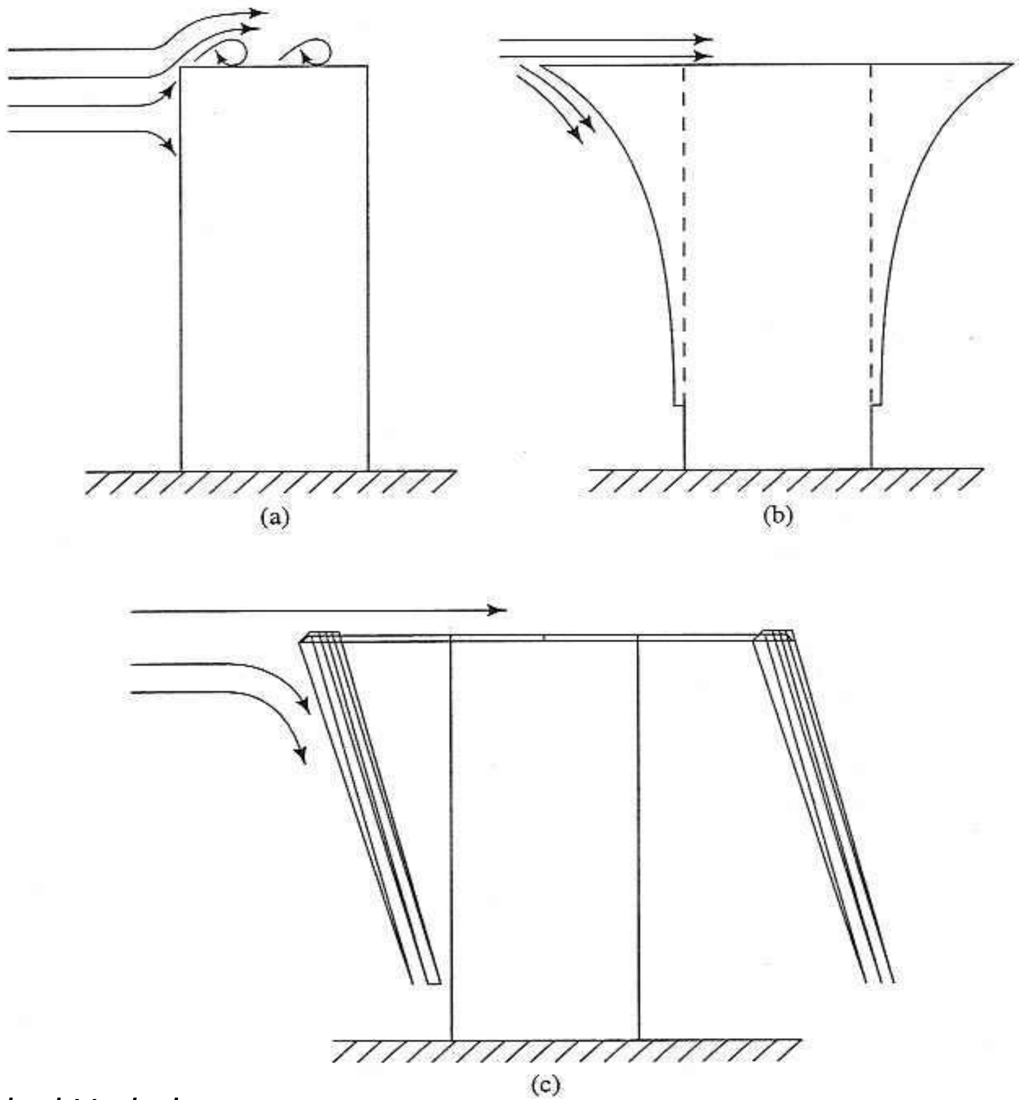
- Wetting losses at the gauge (inside) and in the tank (up to 5-10 %)

- Evaporation of collected precipitation (up to 1-3 %)

(Blow out of collected precipitation (i.e. snow) out of the gauge)

Effect of Wind on Precipitation Measurements

FIGURE 4-15
Wind effects of projecting rain gages. (a) Without wind shielding, upward-moving air in eddies prevents many snowflakes from entering the gage. Rigid Nipher-type shields (b) or hinged Alter-type shields (c) reduce this effect. After Bruce and Clark (1966).



Source: L. Dingman, *Physical Hydrology*

Effect of Wind on Precipitation Measurements

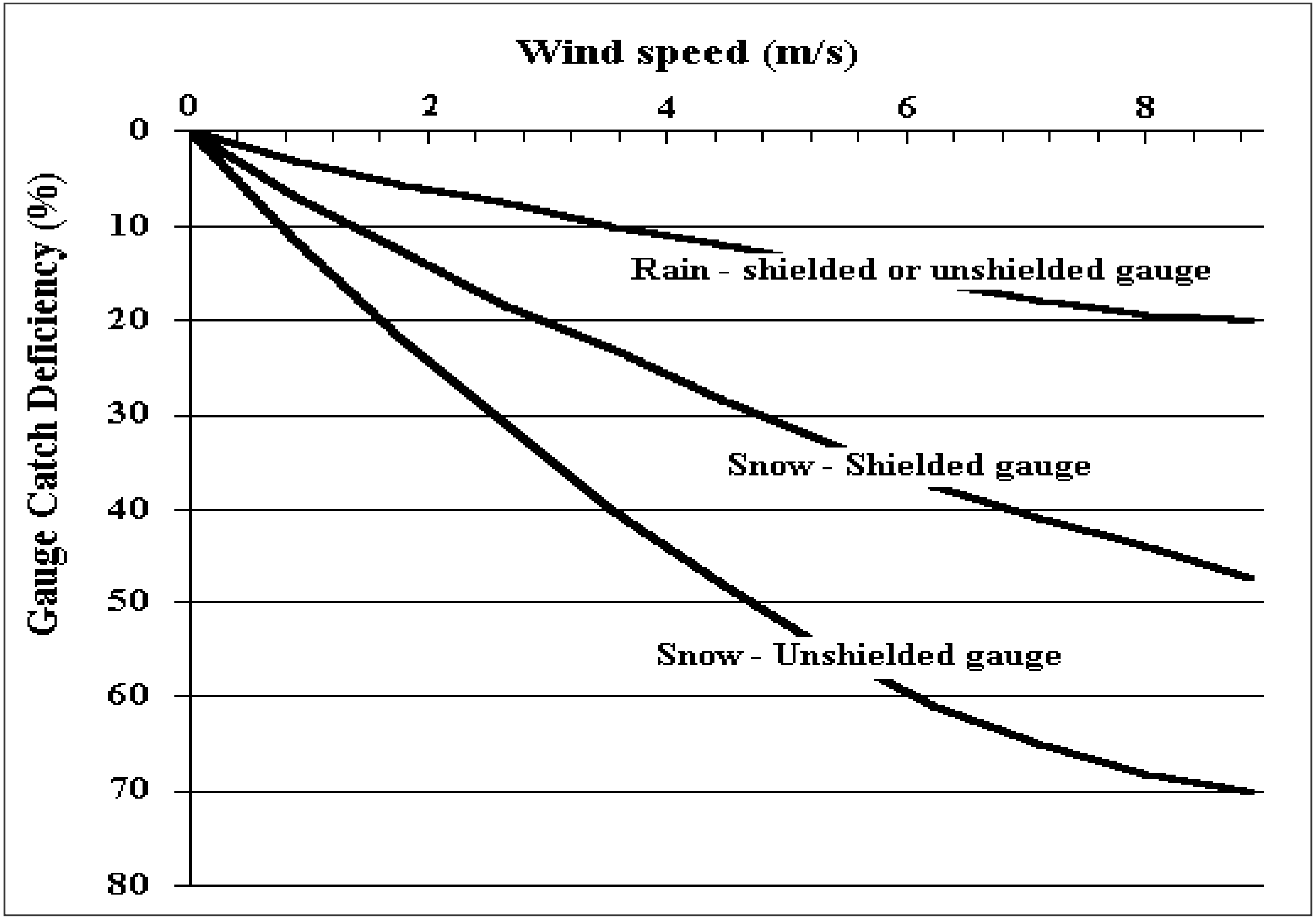
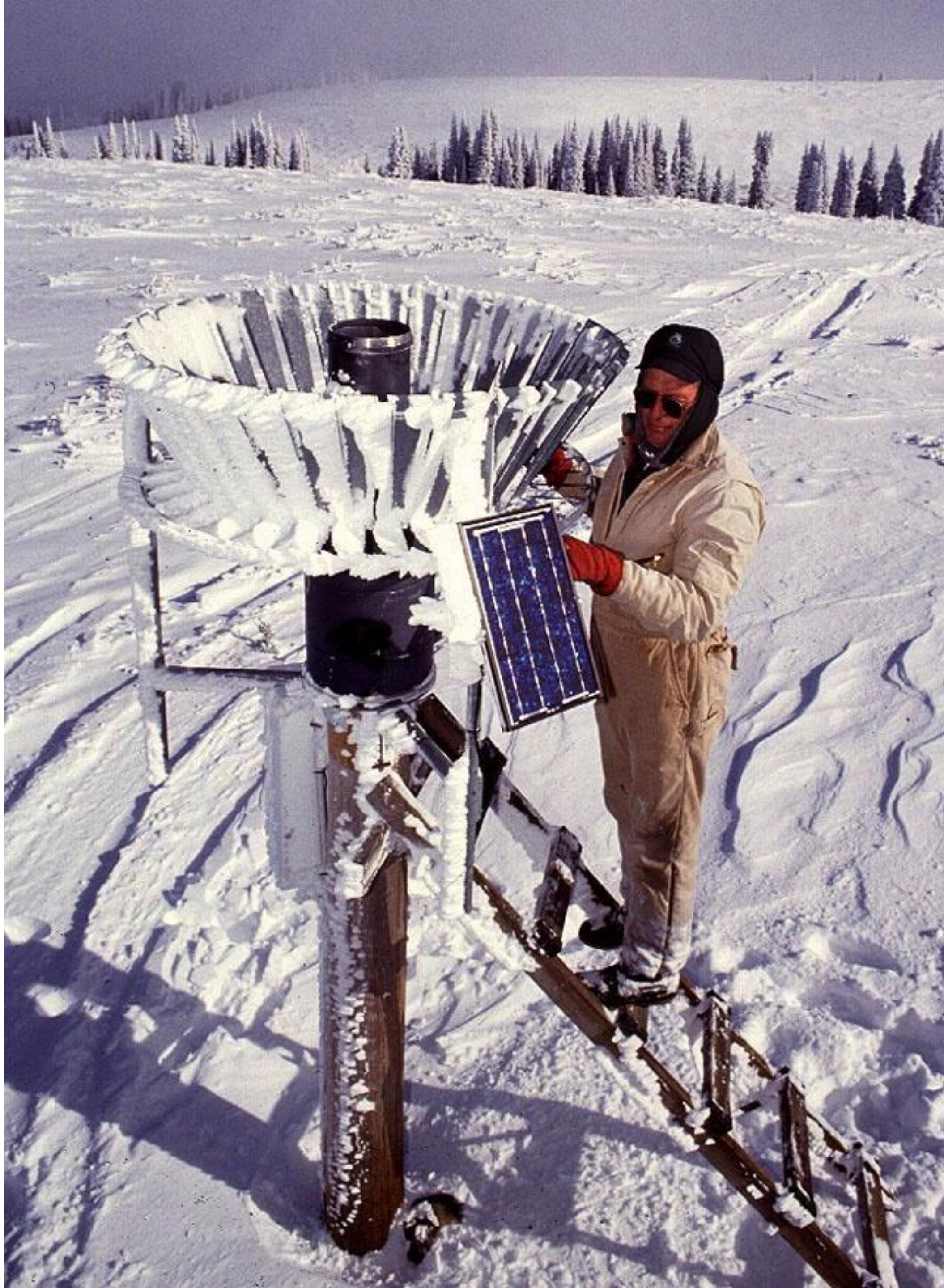


Fig. 2.5 Effect of wind speed on rain catch

Measurement of solid precipitation is *VERY* difficult!

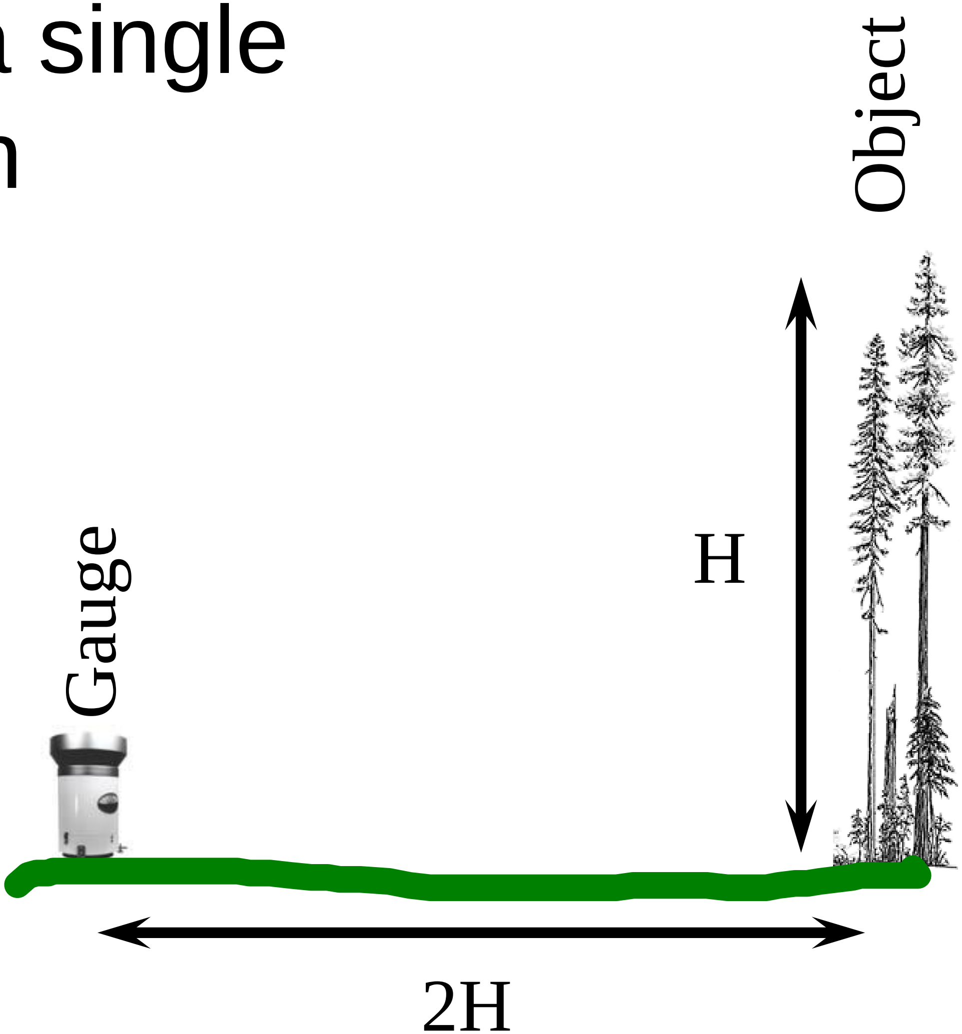
- ***Do you belief me??***

Alter-type Wind Shield



Measuring Rainfall

- A rain gauge is a single point observation
  - Locate away from objects
  - Best if sheltered from wind



Comments …??

Comments …??

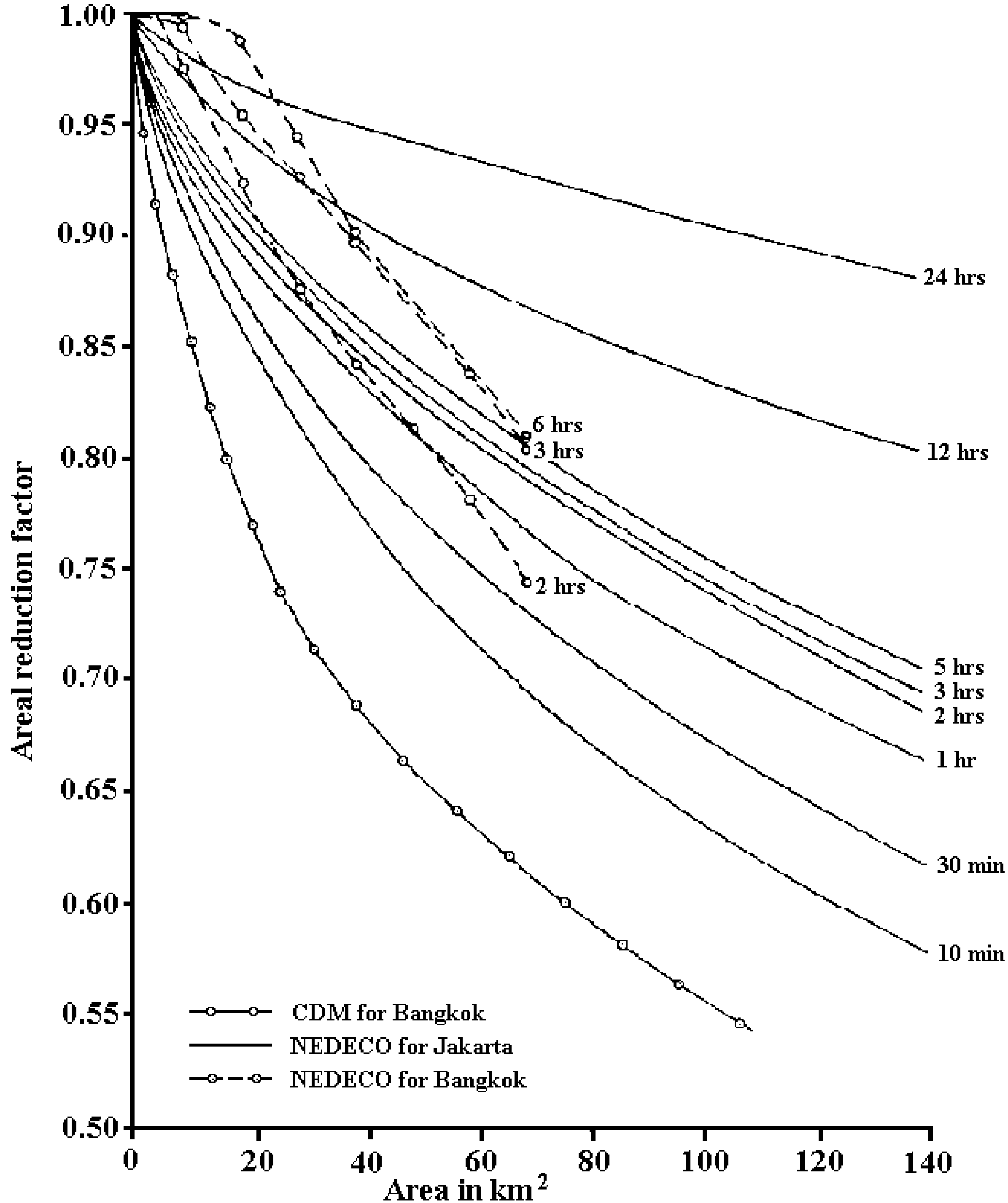
Comments …??

Russian-style wind shield

Heated-orifice gauge

Objectives of this Lecture

- Types of precipitation
- Precipitation formation processes
- Precipitation parameters
- Measurement techniques for precipitation
- Areal estimation of precipitation



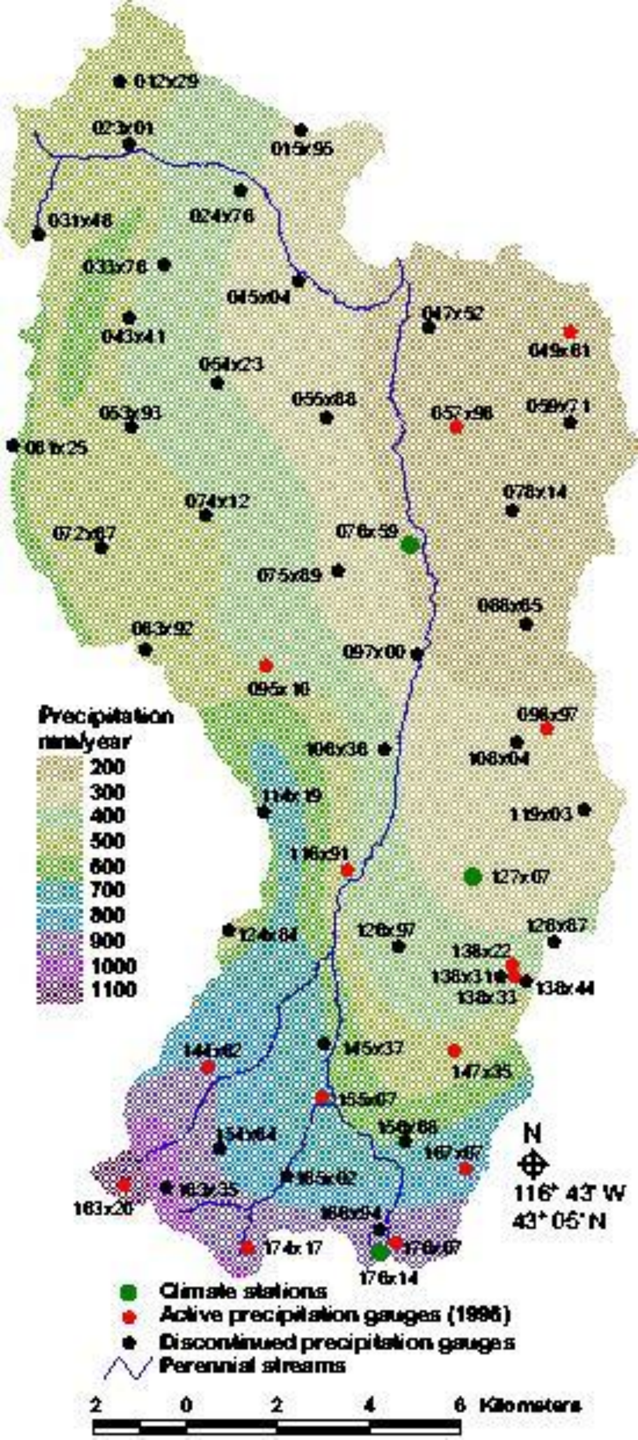
Point rainfall measurements applied to an area have to be reduced:

Areal Reduction Factor, *ARF*

***ARF* depends on rainfall duration**

Estimating Areal Rainfall Distribution

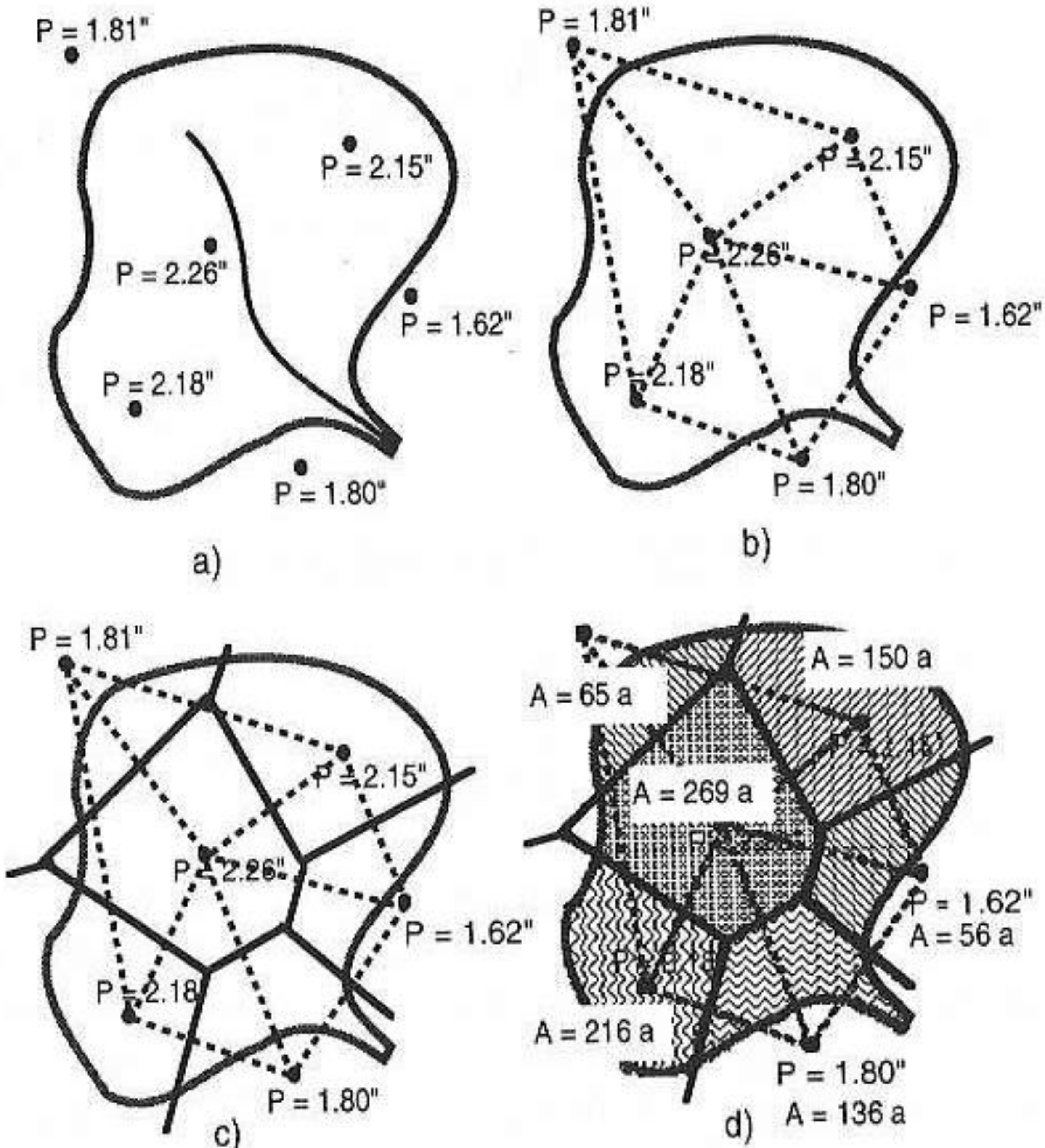
- Large watersheds require a number of gages
  - Limited by costs and time
  - Flat areas need usually fewer stations
  - Consider topographic effects
  - Try to distribute uniformly
    - ➢Access may be a problem in remote areas



Average Precipitation Estimation

- Arithmetic average
  - If gages are evenly distributed and relief is not important
- Thiessen Method/Thiessen Polygons: Weighted average
  - Determine representative area for each gage
- Isohyetal or “contour” area weighted average
  - Draw lines of equal rainfall amounts, like a topographic contour map
- Algorithmic Hypsometric Methods
  - Kriging, Inverse distance weighting, PRISM, ANUSPLIN

Thiessen Polygons



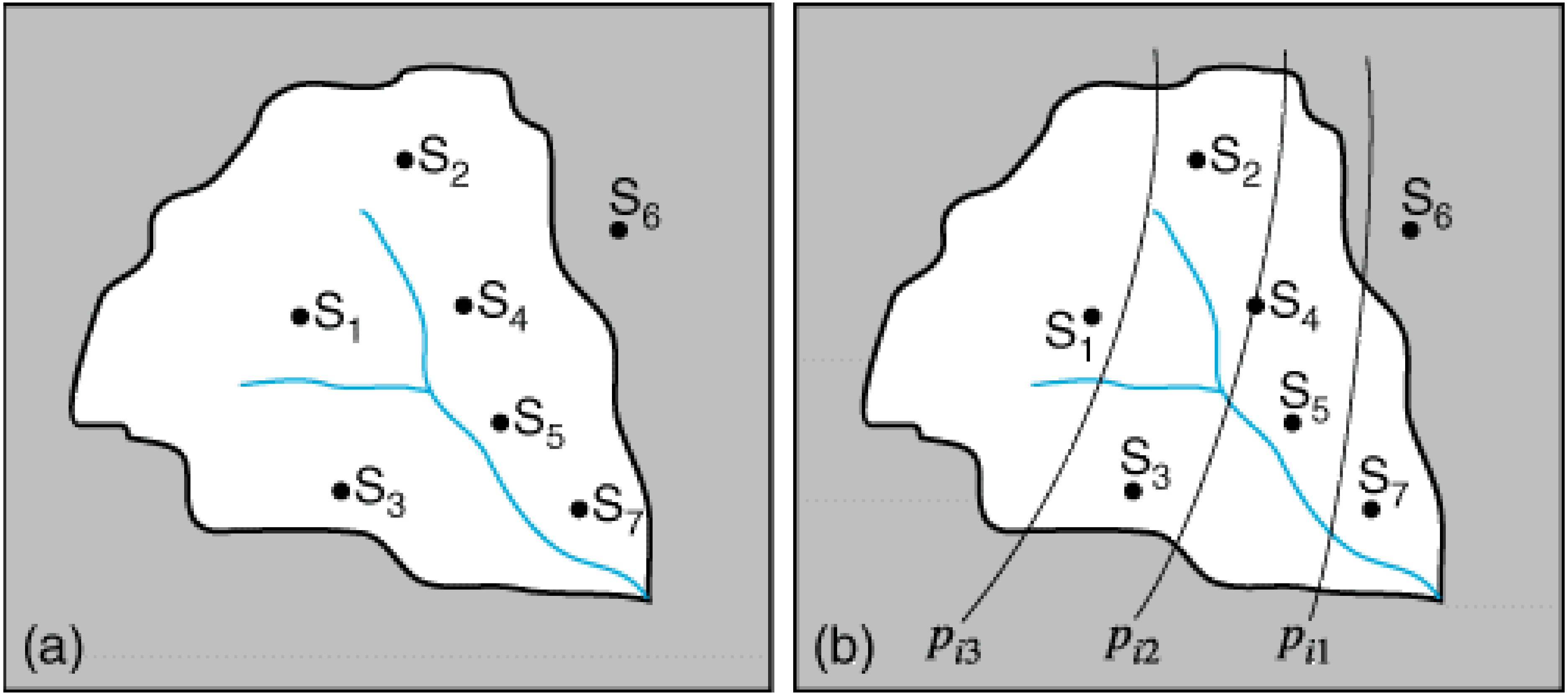
Source: Environmental Hydrology, Ward & Elliot

Example:

How to estimate basin precipitation by area weighted averages?

	Amount, mm	Area, hectar	Weighted amount
	8.81	65	
	12.15	150	
	15.26	269	
	13.18	216	
	5.62	56	
	9.8	136	
Total:			
	(arithmetic mean)	**(Catchment area)**	**(weighted mean)**

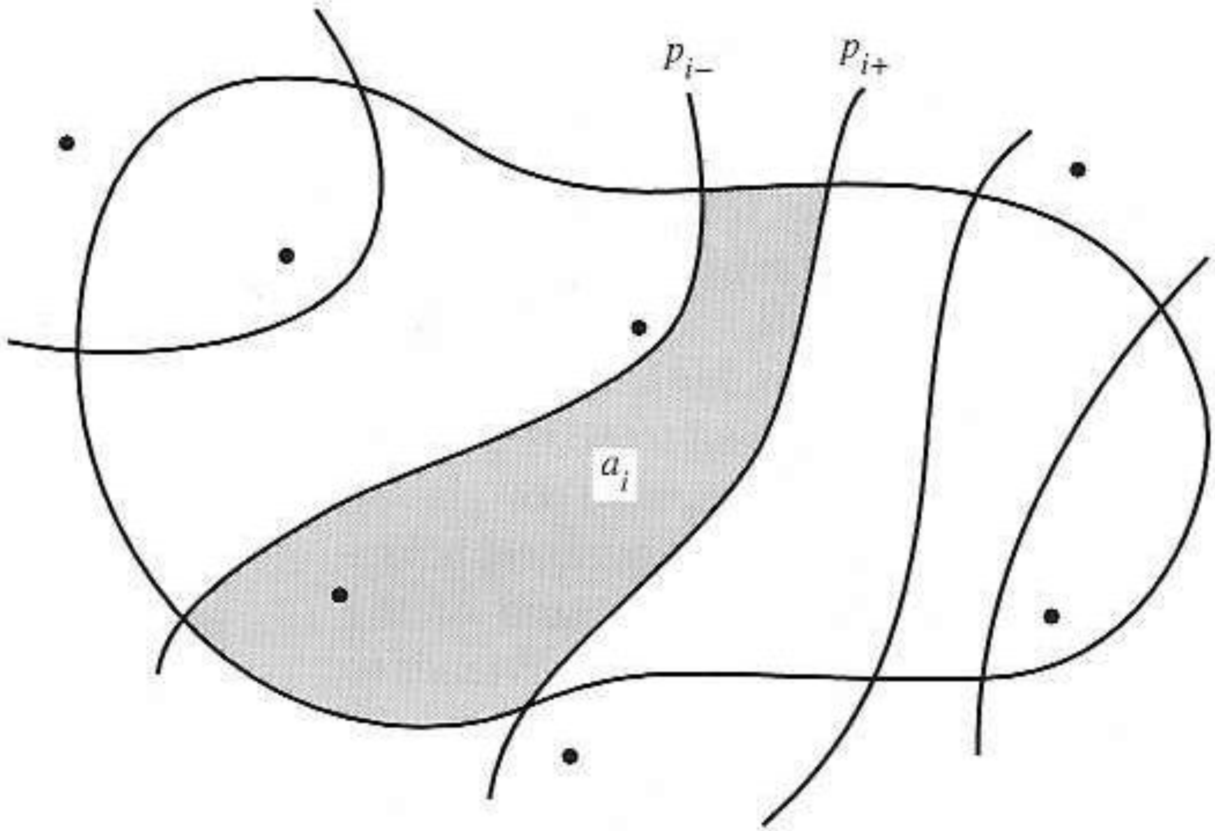
Isohyetal Method



(Hornberger et al., 1998)

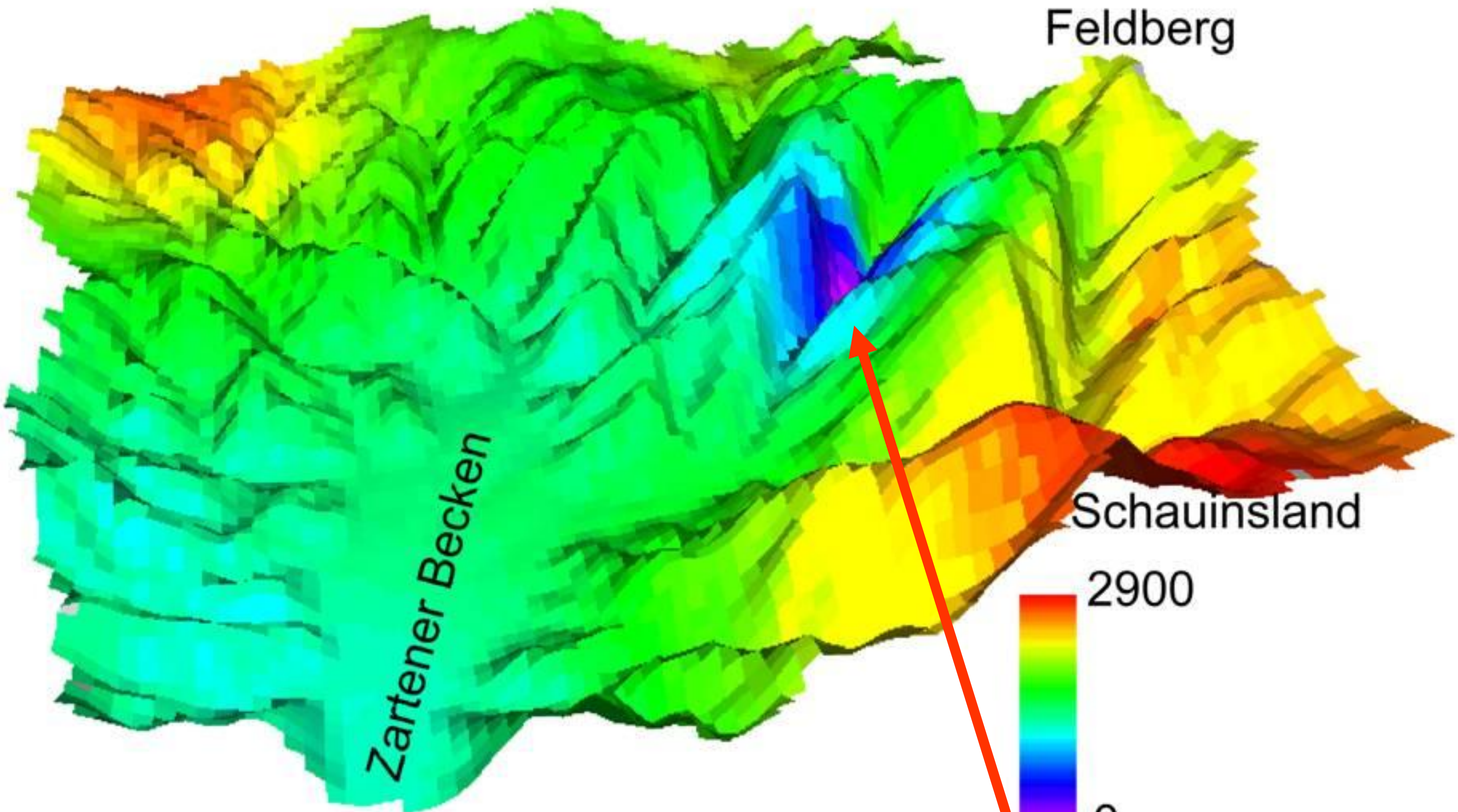
Isohyetal Method

FIGURE 4-26
The isohyetal method of integration. Dots are precipitation-gage locations; thin lines are isohyets; shaded zone is the area a_i between the p_{i-} and p_{i+} isohyets.



Source: L. Dingman, *Physical Hydrology*

Making rainfall maps helps also to control the quality of different stations

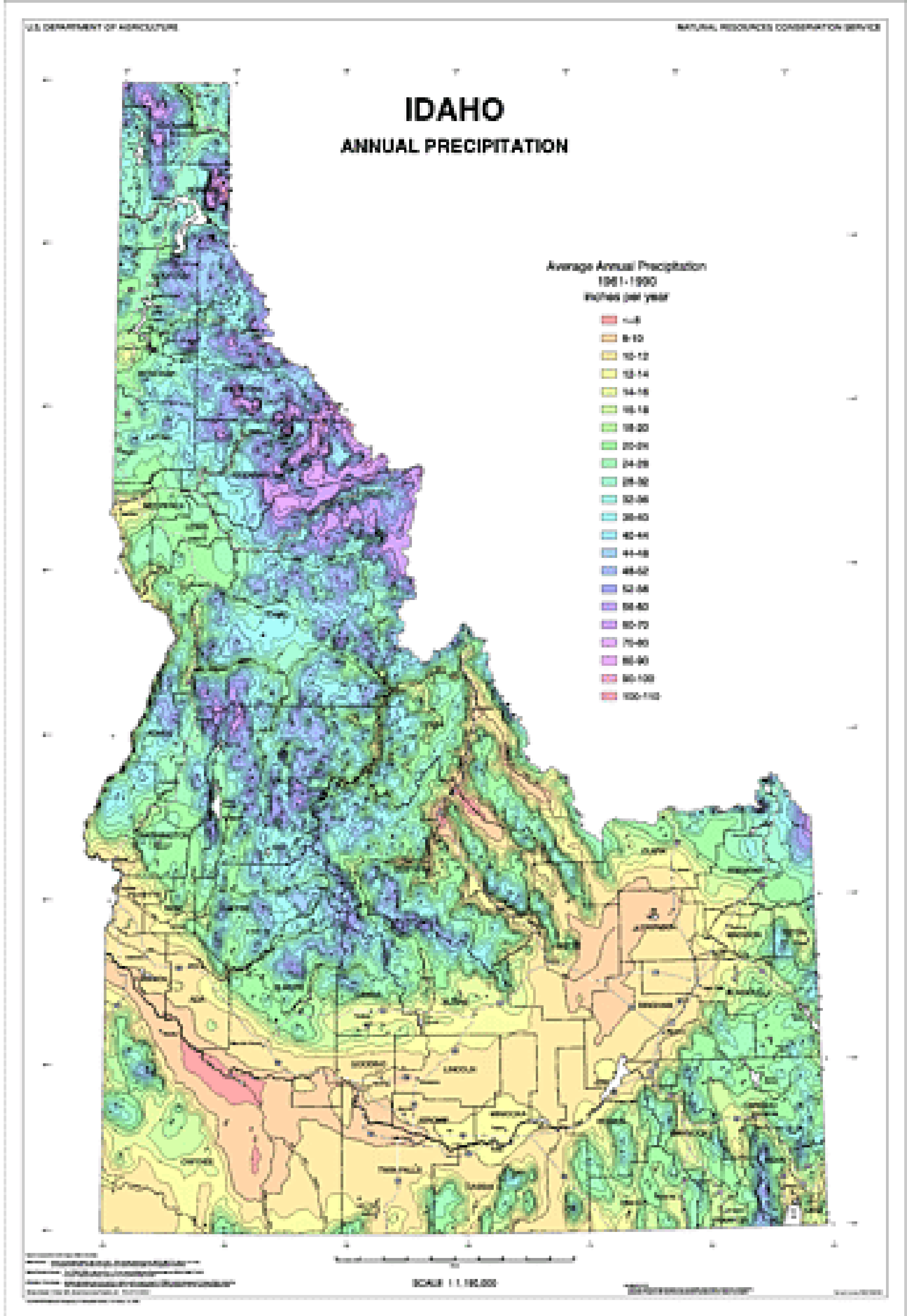


Example from the Dreisam catchment, Black Forest Mountains, Germany

Can this one be correct??

Regionalisation models, e.g. PRISM

PRecipitation-elevation on Independent Slopes Model



Measurement of Areal Distribution of Precipitation

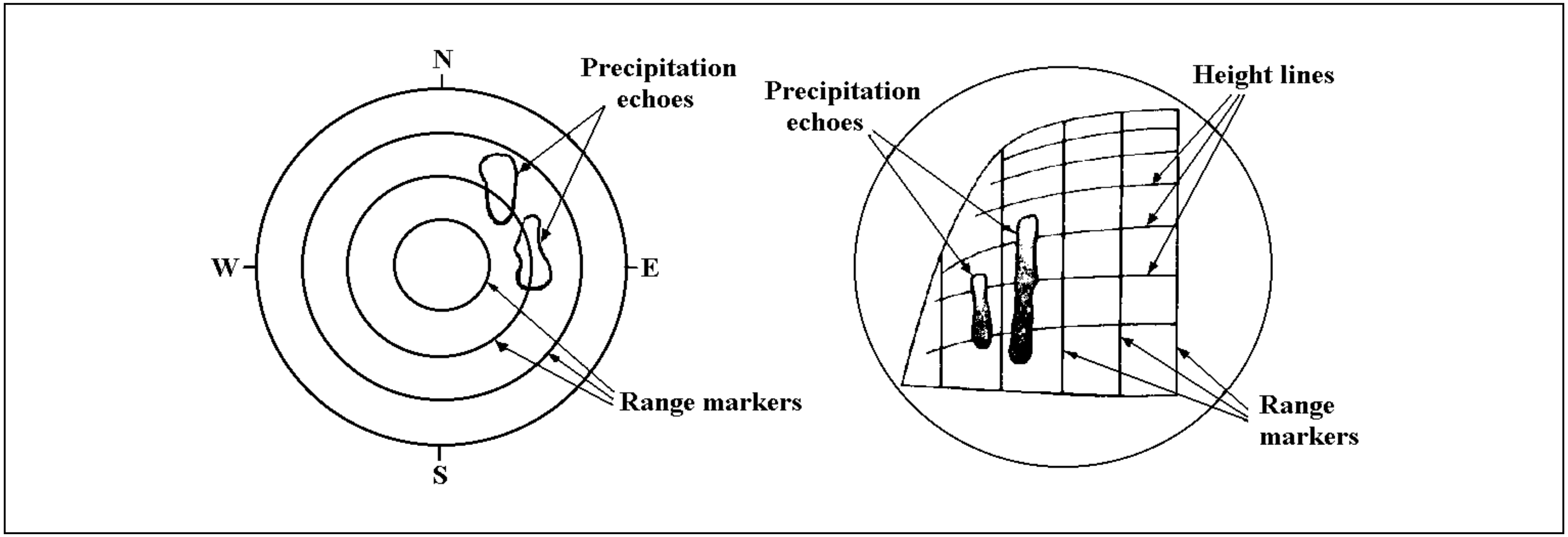
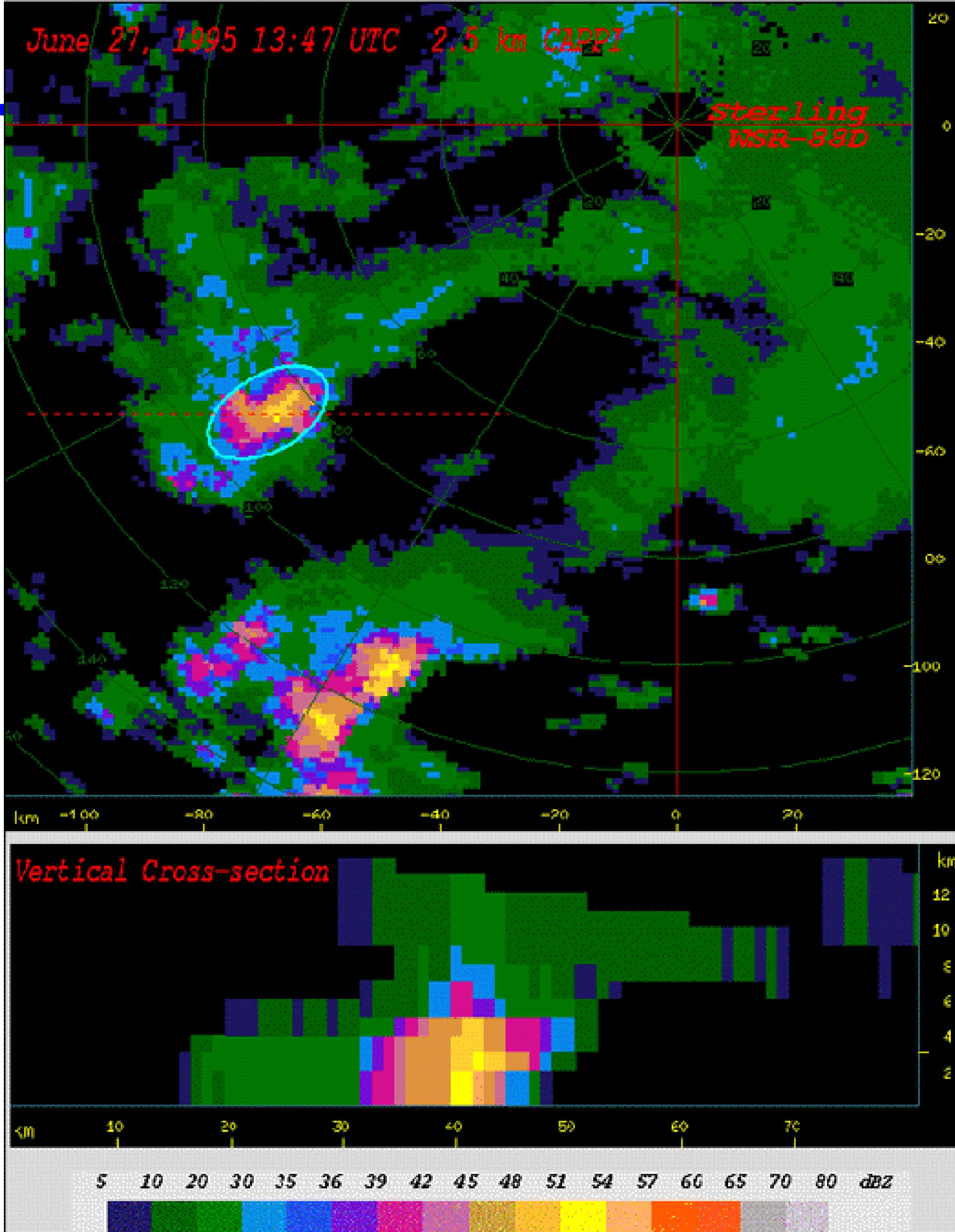


Fig. 2.7 Forms of radar display: PPI (left) and RHI (right)

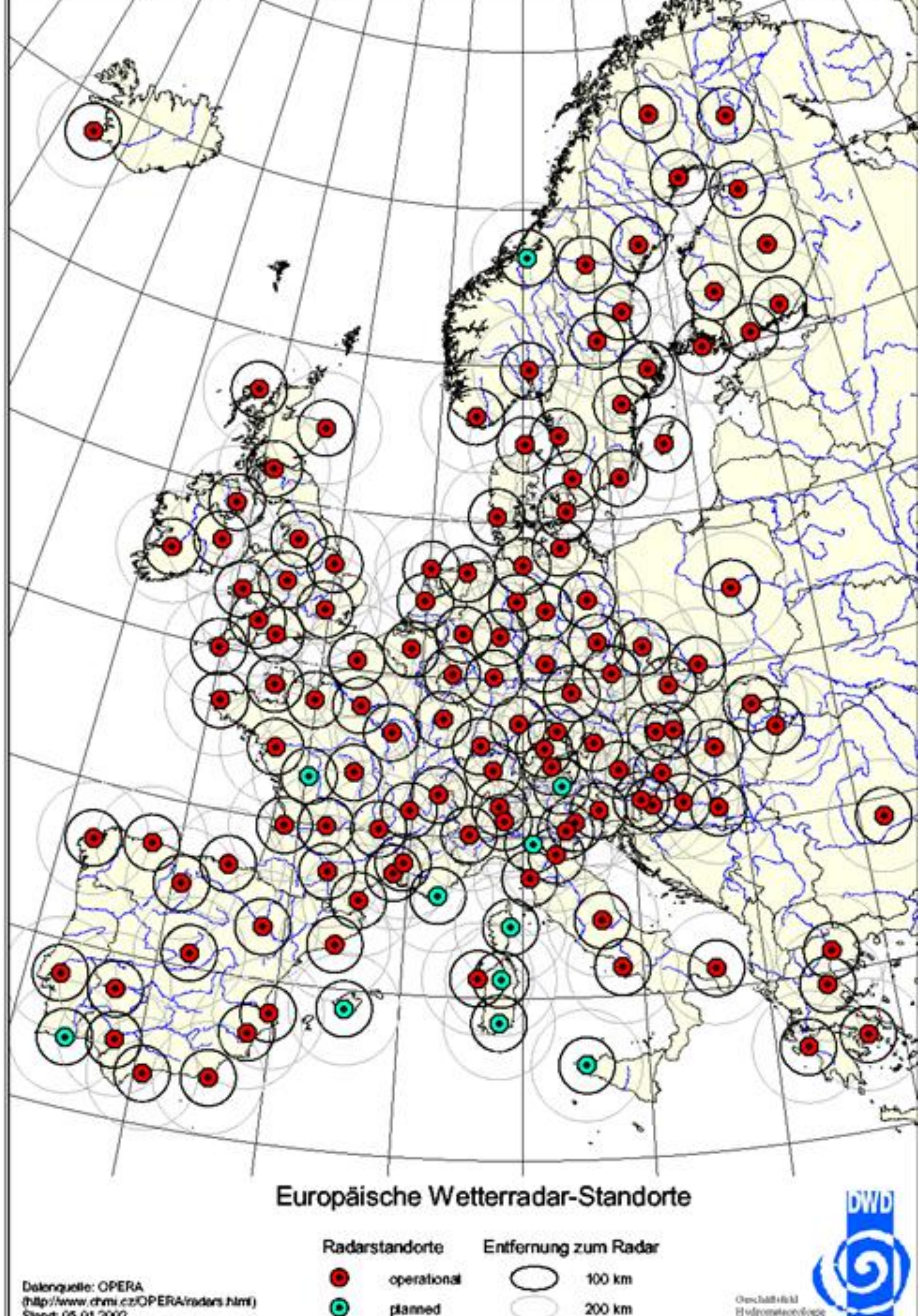
Rainfall Radar

Observation of the space-time variability

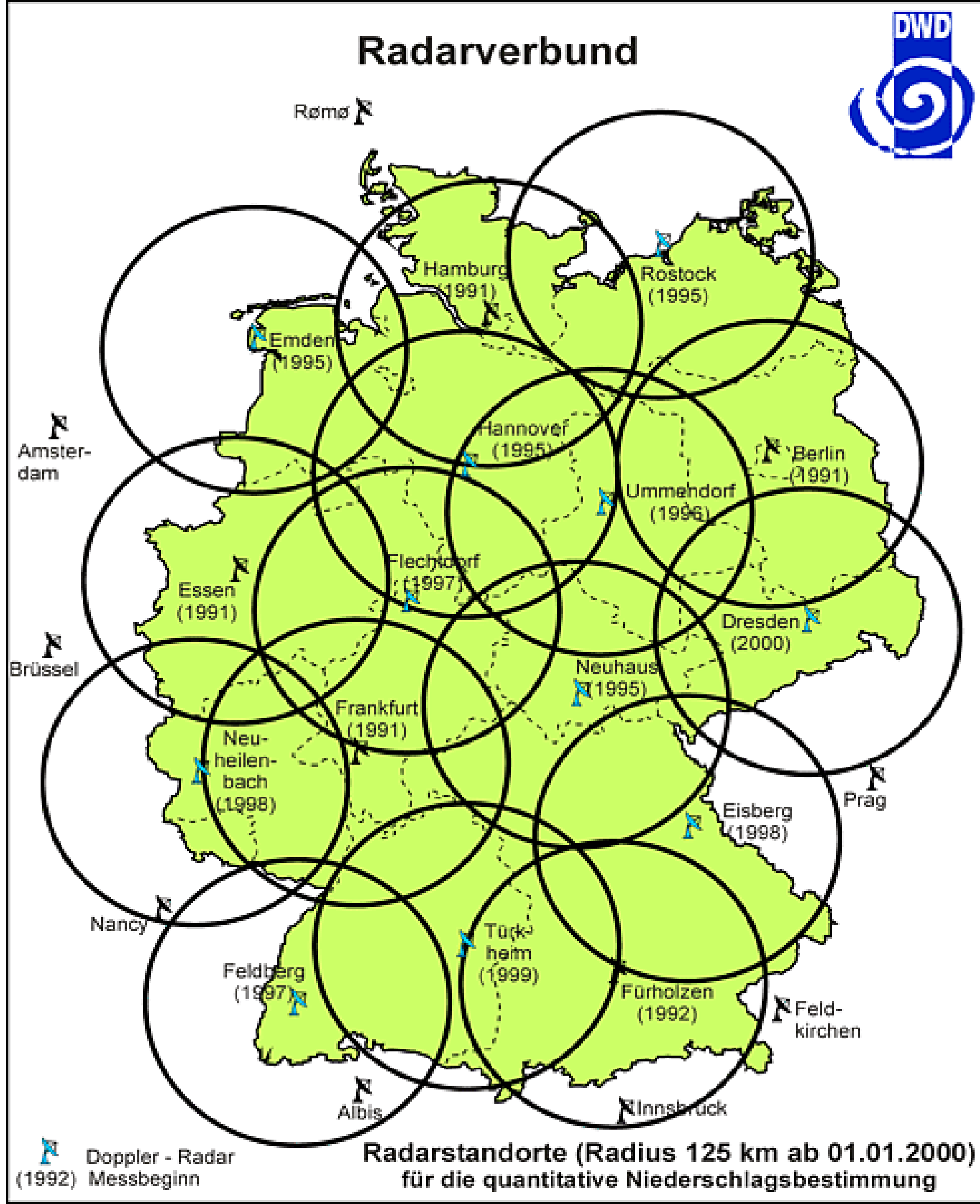


(Aus: Hornberger et al., 1998)

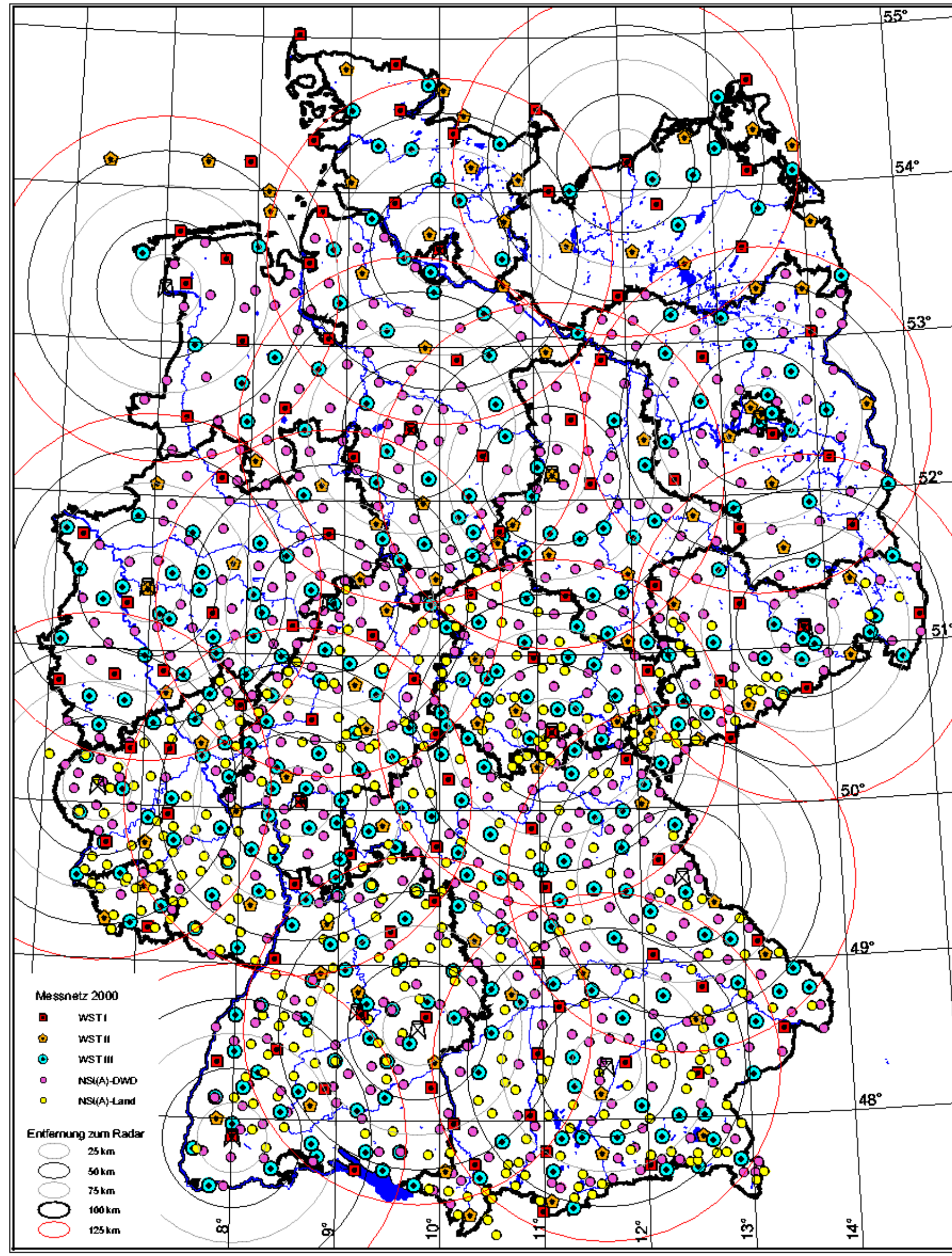
European Rainfall Radar Stations



German Rainfall Radar Stations



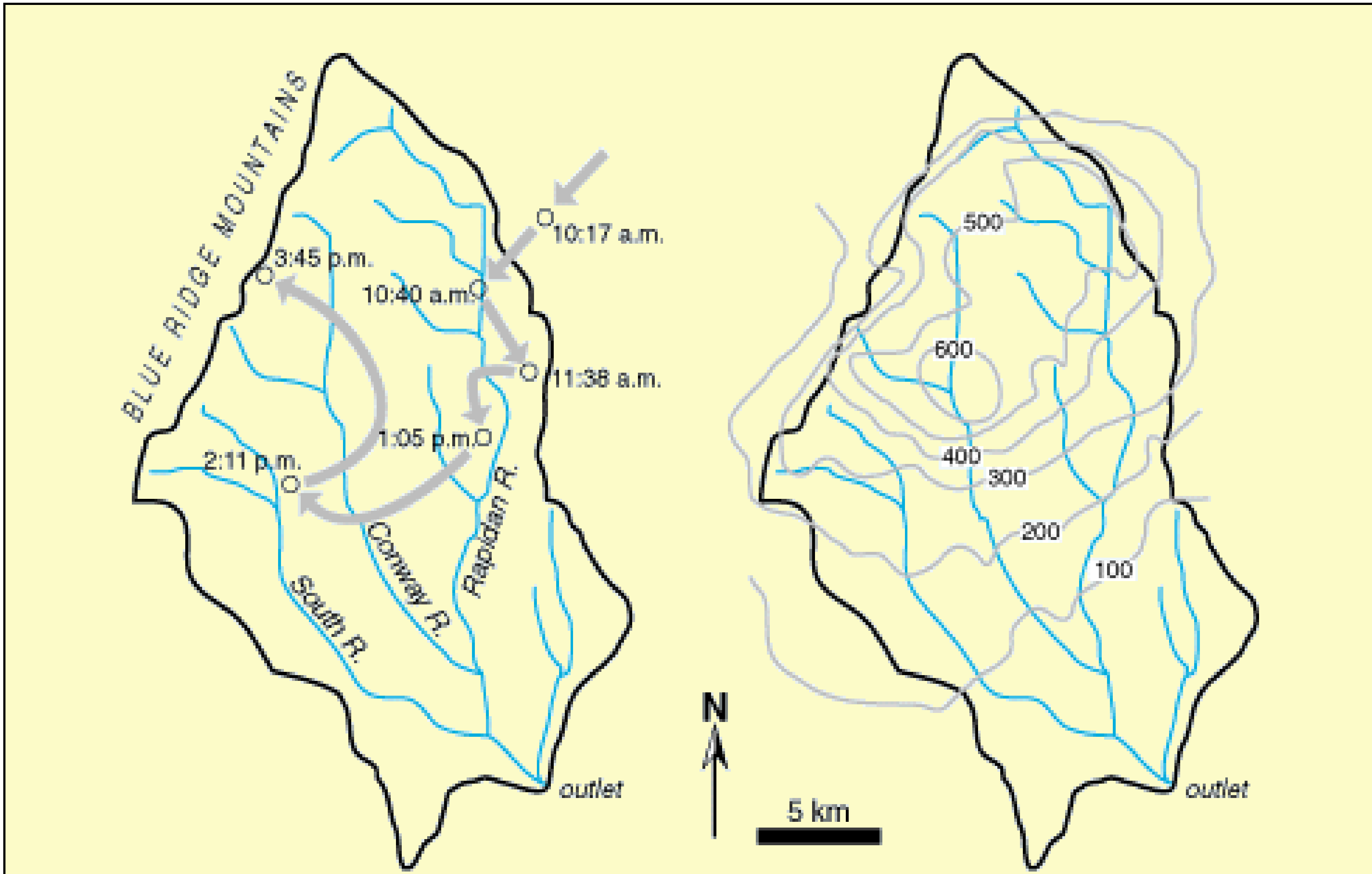
German Rainfall Radar Stations and Automatic Raingauges (on-line)



Automatische Niederschlagsstationen
des DWD und der Länder im Messnetz 2000
(Planungsstand 21.05.2002)

Space-time Variability of Precipitation during a Huge Event in the Blue Ridge Mountains, USA

(values give in mm per event!)



(a) Storm track (b) Total rainfall accumulation

(Hornberger et al., 1998)

Take Home Messages

- Remember the different types of precipitations (often mixtures in reality)
- Main precipitation formation mechanism:
  - (i) convection,
  - (ii) frontal,
  - (iii) orography,
  - (iv) convergence, and
  - (v) cyclones, tropical depressions and hurricanes
- Characterization of precipitation through different parameters
- Measurement of precipitation (devices and techniques)
- Areal estimations of precipitation (different methods); when is which method appropriate?

Brief Introduction to Frequency Analysis

$P(X>X_0)$ — Probability of exceedance, probability that X is greater than or equal to X_0; $0 \leq P \leq 1$

$T(X>X_0)$ — Return Period or average recurrence interval, the average (!) time in years between the occurrence of an extreme event X

T and P are as follows related

$$T = \frac{1}{P}$$

Probability the event will not occur next year

$$\left(1 - \frac{1}{T}\right)$$

Probability the event will not occur the next N years

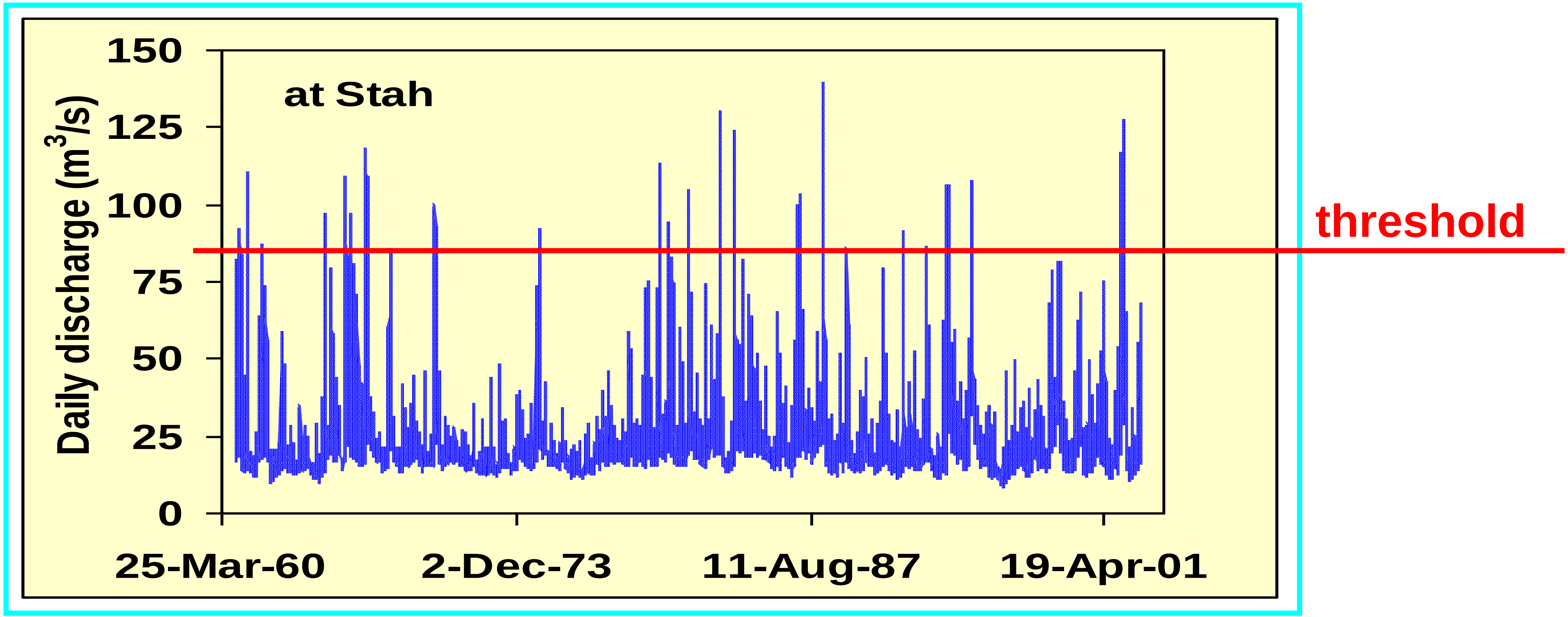
$$\left(1 - \frac{1}{T}\right)^N$$

Probability the event occurs at least once in the next N years

$$P = 1 - \left(1 - \frac{1}{T}\right)^N$$

Frequency analysis (e.g. peak flows)

- Annual maximum series (more common)
  - One can miss a large event if more than one large event per year; but continuously/consistent and easy to process
  - Often used for estimating extremes in long records (>10 years)
- Partial duration series ("Peaks-Over-Threshold, POT")
  - Definition of the threshold is tricky and requires experience
  - Often used for short records (<10 years)



Flood frequency analysis (peak flows):

Annual max. series

vs.

partial duration series

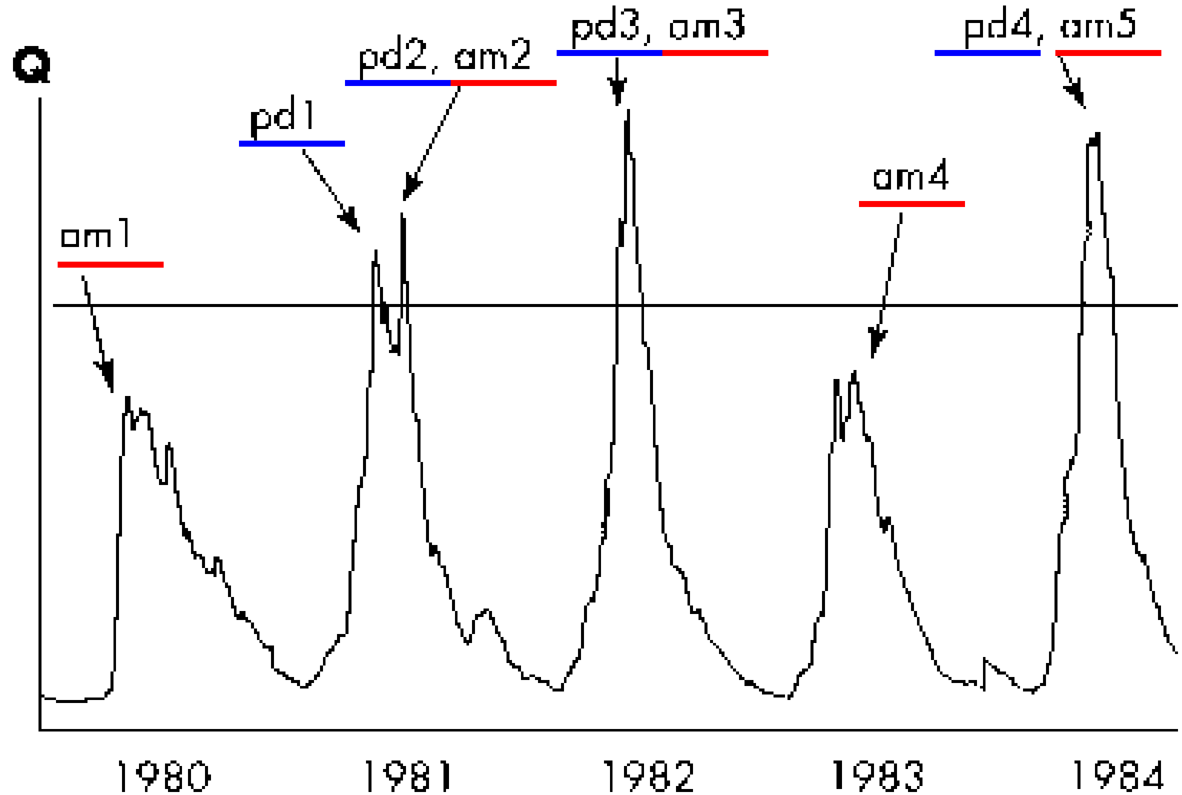


Figure 7.10 Daily flow record for the Adams river (British Columbia, Canada) during five years in the 1980s. Annual maximum series are denoted by 'am', partial duration series above the threshold line by 'pd'. NB In this record there are five annual maximum data points and only four partial duration points, including two from within 1981.

Source: Data courtesy of Environment Canada

(Davie, 2002)

Annual max. series *vs.* partial duration series (POT)

- Langbein showed the following relationship (Chow 1964):

$$1/T = 1 - e^{-(1/T_p)}$$

T : return period using annual max. series

T_p: return period using partial duration series

- Differences get smaller for larger return periods (less than 1% difference for a 10-year recurrence interval)!

Given data: Annual maximum daily rainfall of 10 years (N = 10)

Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
mm/d	56	52	60	70	34	30	44	48	40	38

Rank values in descending order

m Rank	Rainfall amount (mm)	p Probability exceedence	T Return period
1	70	0.09	11.0
2	60	0.18	5.5
3	56	0.27	3.7
4	52	0.36	2.8
5	48	0.45	2.2
6	44	0.54	1.8
7	40	0.64	1.6
8	38	0.73	1.4
9	34	0.82	1.2
10	30	0.91	1.1

Estimate probability of exceedance:

$$\cancel{p = \frac{m}{N}}$$

Weibull:

$$p = \frac{m}{N+1}$$

Gringerton:

$$p = \frac{m - 0.44}{N + 0.12}$$

More on Gumbel and other distributions during the workshop exercises!