Spring School on Fluid Mechanics and Geophysics of Environmental Hazards
19 Apr – 2 May 2009

Institute for Mathematical Sciences

EXTREME RAIN AND WIND STORMS IN THE MID-LATITUDES:

a problem of possible maximum precipitation

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1: THE PROBLEM

The aim is to derive the possible maximum precipitation that could occur over a 24 hour period on the mountain range in figure 1: a 2-dimensional mountain range with a crest height of 2km and linear slope of 1:25.

Consider an air column of 12km height at the foot of the mountain (i.e.: has not begun ascent). The temperature at the bottom of the column (i.e.: the surface temperature) is 21°C and at all levels the air temperature (T) equals the dew point temperature (Td). There is a horizontal wind of 20m/s that is constant with time at all levels.

What is the possible maximum precipitation that could occur over a 24 hour period?

Three assumptions are made: (1) ALL condensed water falls vertically to the ground as precipitation, exactly at the position where it was produced in the column; and (2) the flow is steady with a supercritical Froude number (F >> 1). (3) The horizontal wind speed is constant with height ($du/dx \neq 0$), as is the vertical updraft ($dw/dx \neq 0$)

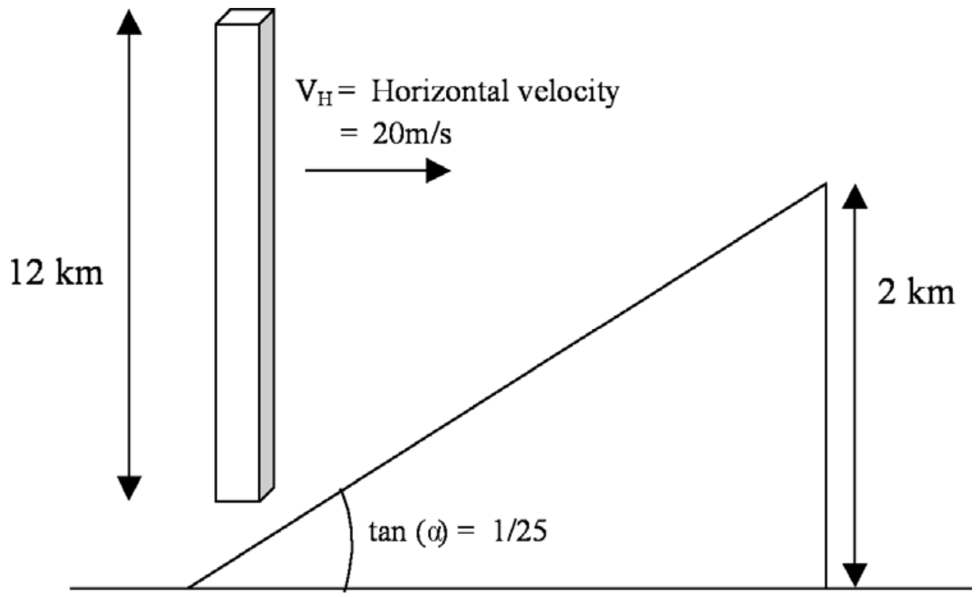

Figure 1. Orographic lifting of air column with constant horizontal velocity (Vh)

2: THE APPROACH

To derive the volume of moisture in the column, Q (specific humidity), the temperature (T) must be known.

So we face the first challenge: what is the vertical profile of T?

We know that T at the surface is 21°C, and that T follows the moist adiabatic lapse rate (because T = Td at all levels). The moist adiabatic lapse rate is given by:

$$(1) \qquad \frac{dT}{dZ} = \frac{-g\left(1 + \frac{LQ}{TR}\right)}{Cp + LQ\frac{1}{E}\frac{dE}{dT}}$$

Equation 1. The moist adiabatic lapse rate

This is a complex equation and difficult to integrate over the height of the column. Consequently, we use an iterative approach to "reinvent" the moist adiabatic lapse rate. This numerical approach is outlined in figure 2; a flow chart describing each quantitative step to approximate the amount of water vapor in the column.

3: THE CALCULATIONS

To solve for the specific humidity, Q, at each level, the saturation vapour pressure, E, is required. E varies exponentially with T, as illustrated by the Claussius-Clapeyron Equation. It is approximated by the Magnus Teten Equation (Equation 2):

$$(2) \qquad \log_{10} E = \frac{7.5T}{T + 237.3} + 0.7858$$

Equation 2. The Magnus Teten Equation

Using equation 3, Q is solved.

$$(3) \qquad Q = \frac{\rho_{water}}{\rho_{air}} = \frac{R_{air}}{R_{water}}\frac{E}{p} = 0.622\frac{E}{p}$$

Equation 3: Specific humidity, where R is the gas constant for air (267) and water (461)

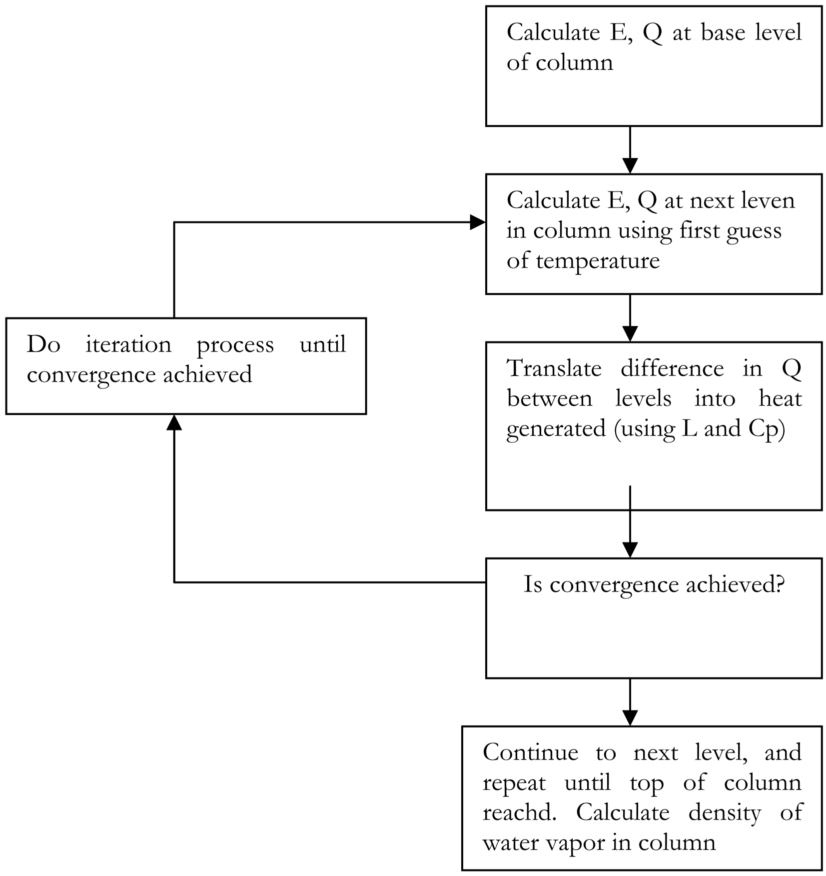

Figure 2. The approach used to calculate the amount of water vapor in the column. E is the saturation vapour pressure. Q is the specific humidity. L is the latent heat of vaporisation. Cp is the specific heat capacity of air at constant pressure.

3.1: Q at the Surface

Using equations 2 and 3, Qsurface is calculated.

T = 21°C , P = 1000 hPa

E = 24.86 hPa

Qsurface = 15.6 g/kg

As an iterative approach to solving this problem has been adopted, Q and T at the next height level must be solved. Thus consider z = 500m.

3.2: Q at 500 Metres

At 500m we know that the air pressure is ~ 940hPa, however we do not know the air temperature.

Let us assume at z = 500m the temperature is 18°C.

3.2.1: First Guess, T = 18°C

With equations 2 and 3, Q500m is calculated using T =18°C (i.e.: a 3°C drop in T):

T = 18°C* , P = 940 hPa *first guess

E = 20.63 hPa

Q = 13.7 g/kg

ΔQ (500m – surface) = -1.9 g/kg

This is condensed water vapor of Q = 1.9 g/kg is released as latent heat and makes the environmental temperature increase by an amount calculated by equation 4.

(4) $$\frac{L\Delta Q}{Cp} = \text{Heat Released (°C)}$$

L is the latent heat of vaporisation ~ 2256 × 10^3 J/kg
Cp is the specific heat capacity of air at constant pressure ~ 1000 J/kg

From equation 4, ΔQ = -1.9 g/kg warms the environment by 4.3°C. As the vertical temperature profile must follow the moist adiabatic lapse rate, equation 4 reveals that the temperature of an 18°C parcel of air at 500m would be 22.3°C at the surface rather than 21°C.

This excess of 1.3°C translate to second guess of T500m of 19.3°C.

3.2.2: Second Guess, T = 19.3°C

Using equations 2, 3 and 4, the following is found:

T = 19.3°C** , P = 940 hPa ** second guess

E = 22.33 hPa

Q = 14.78 g/kg

$\Delta Q = 0.82$ g/kg

Heat Released = 1.85°C (19.3 + 1.85 ~ 21 , good!)

Therefore, T500m ~19.3°C, Q500m ~ 14.78 g/kg.

This iterative process continues up to the top of the column, at which point the vertical profile of Q and T is known when the column of air is at the foot of the mountain. The next step is to introduce time and advect the column over the mountain.

4: INTRODUCING TIME

As the column of air moves across the mountain at 20 m/s, it rises at 0.8 m/s (as the slope gradient is 1/25). For every 100 seconds the air column is displaced 80m vertically (see figure 3) and the temperature of the column reduces (as T reduces with height). Condensation occurs which, under the stated assumptions, is considered as precipitation.

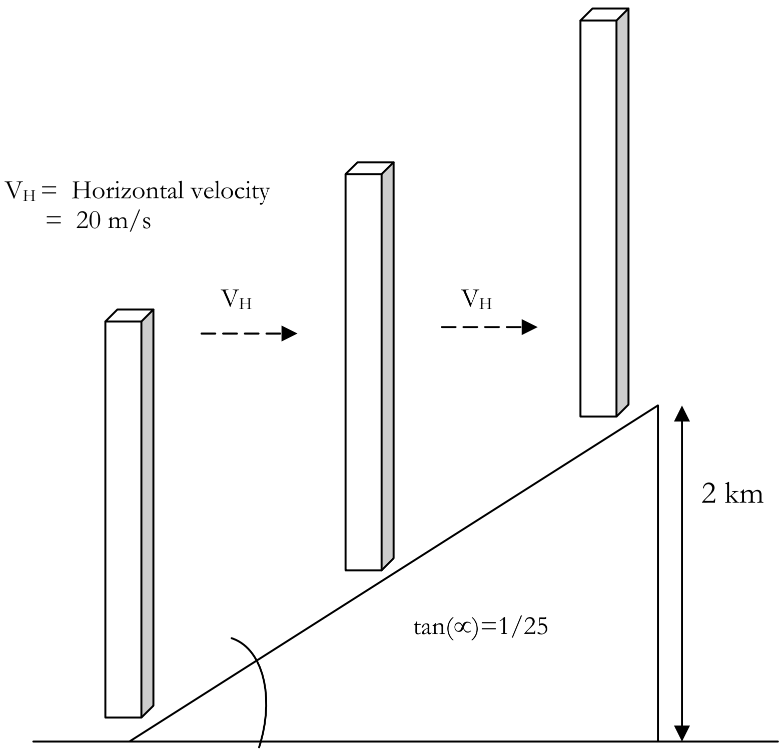

Figure 3. The advection of air column with horizontal velocity of 20 m/s and vertical velocity of 0.8 m/s.

5: RESULTS

A programme using MATLAB was created to make the many iterative calculations required. Vertical profiles of T and Q were solved at three different stages of the air column being advected over the mountain: the start (vertical displacement, z = 0km), middle (z = 1km) and top (z = 2km). Results in figure 4.

As the air column ascends the mountain, T and Q both reduce. Q decreases because the atmosphere has a reduced ability to hold moisture at lower temperatures and excess water vapour condenses and becomes precipitation. Precipitation is highest at the bottom of the mountain, where Q is greatest, and reduces thereafter.

QuickTime?and a
decompressor
are needed to see this picture.

Figure 4. The vertical profile of T and Q at three different locations on the mountain: z = 0km, z = 1km and z = 2km.

Figure 5 shows how precipitation reduces with mountain height if derived by this iterative process. [Results in figure 5 from identical scenario except the mountain is 100km wide rather than 50km, halving the slope angle.]

Figure 6 shows the effect of a change in vertical velocity on precipitation. When the slope of the mountain doubles, the vertical velocity doubles. With the assumption of ALL condensed water falling vertically as precipitation exactly at the position it was created, doubled vertical velocity creates doubled precipitation. This highlights the significant influence updrafts have on precipitation.

Figure 6 also shows the effect of wind drift on precipitation. An assumption was made that the condensed water falls to the ground EXACTLY at the position it was created. In reality, the horizontal wind will advect the precipitation some distance, changing its spatial distribution.

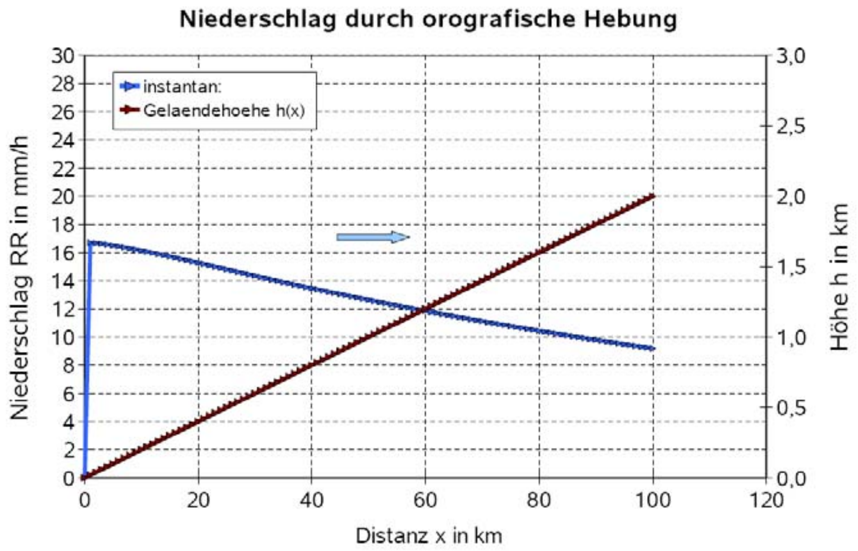

Figure 5. Horizontal profile of precipitation (blue) and the mountain height (red).

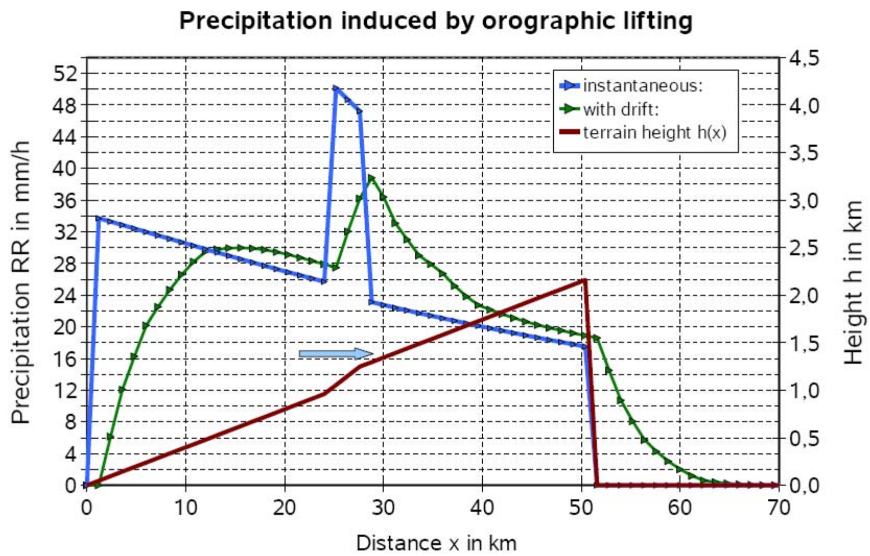

Figure 6. Horizontal profile of precipitation without wind advection (blue), precipitation with wind advection (green) and the mountain height (red).

6: CONCLUSION

This highly idealised scenario makes a number assumptions that do not hold in the real world, and it is important to be aware of this drawback. It highlights, however, the possible maximum precipitation over a simplified terrain and can be useful in making a first guess of potential flood damage.

APPENDIX

Characteristics of Rainfall in Sumatera, Indonesia

West Sumatera is located in the middle of western part Sumatera Island. As we see in Fig 7, it`s looks that Sumatera Island divided 2 region by mountain range. This mountain range we call by Bukit Barisan. The sea breeze from Hindia ocean effects to the west part of Sumatera Island and make this region has much rain. Eastern part of Sumatera facing with malacca strait, this region more dry than the West part of sumatera. Cloud formation move from Hindia ocean to West pasific and become weak in the east part of Sumatera, this probably cause by blocking effect of Topography. We can see such kind this effect in fig 8. A considerable part of west sumatera is plateau and mountainous region. Because of the illegal logging in this region made the land condition of this region become unstable, and have oportunity of landslide and flood. Threatening of landslide is serious problem for the people who living in mountainous region.

Measurement of rainfall in mountainous region is very usefull. We will know the effect of topography to the distributing of rain in mountainous region of West Sumatera. The aim of this study is to know the distibuting of rain, the speed and direction of surface wind in west slope, peak and north slope of mountain region. And this study also want to compare rainfall data that taken from raingage with Xband radar data.

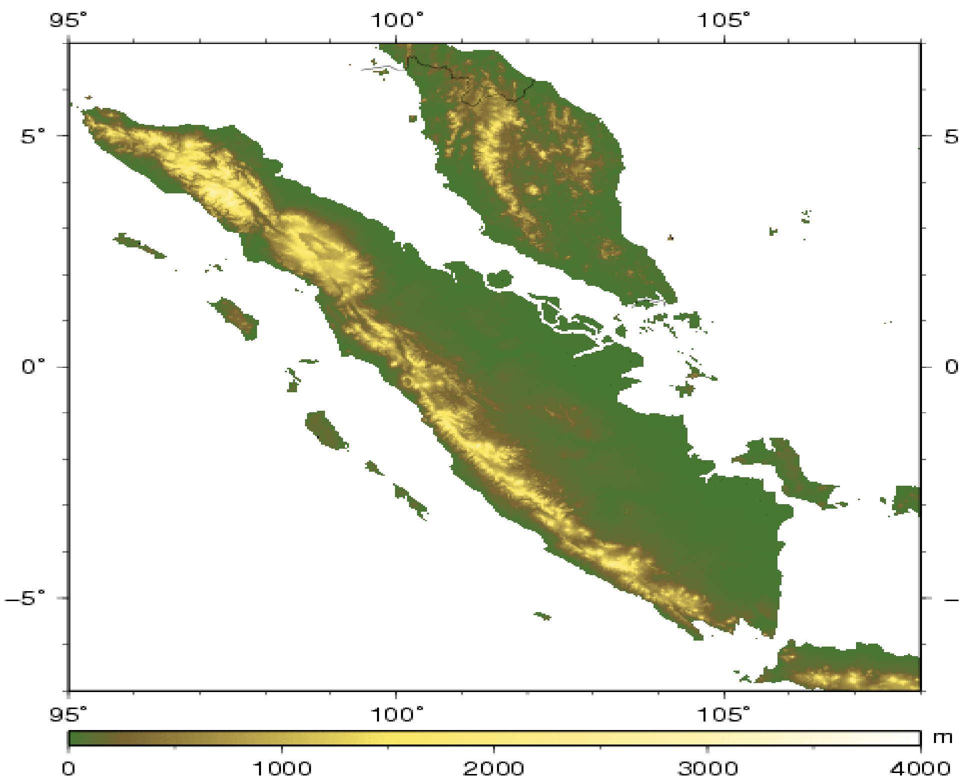

Figure 7. Sumatera Island

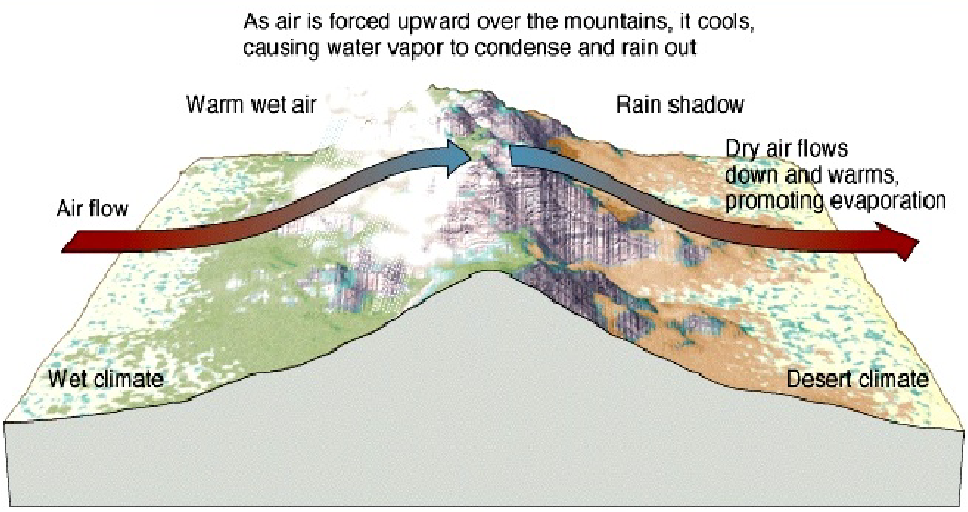

Figure 8. Blocking effect of topography (Smith et al.1997)

Measured rainfall data from 7 raingage in different location for three years have shown in Fig 9. In 2003 shows that small rainfall occured in Tiku (coastline). Rainfall amount become more bigger in Sicincin (West slope of mountain range). The rainfall decrease in Padangpanjang, Matur, Kototabang, Biaro and Tanjung pati. Different with 2003, in 2004 Tiku has much rain than the year before. But the amount of rainfall still lower than Sicincin. Similar with 2003, rainfall decreased in Padangpanjang, Matur, Kototabang, Biaro and Tanjungpati. Sicincin still has much rain in 2005. Padangpanjang has no much rain in this year but accumulation of rain become much bigger in Matur. Others area have small amount of rainfall than area which explained before. We can see in Fig 9, that the amount of rainfall in Sicincin always more bigger than others area, and Biaro always has less than the others.

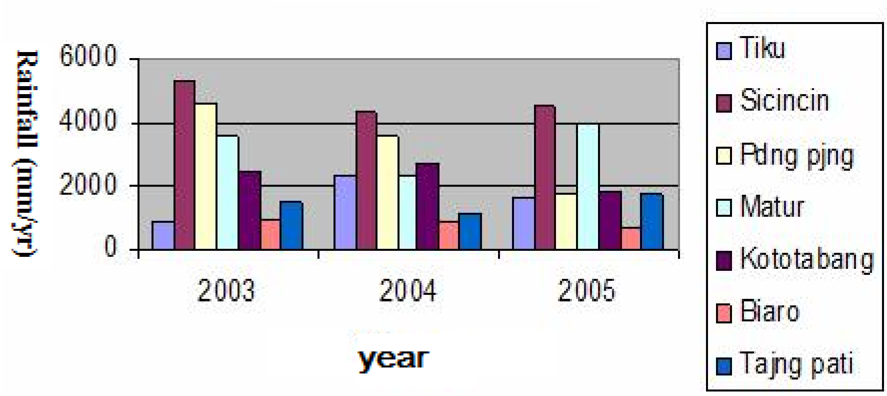

Figure 9. Rainfall distribution from 7 raingauge

Figure 9 shows the distribution of rainfall based on surface topography. Sicincin which located in the west part of mountain region (slope mountain) has much rain, then rainfall become decrease when surface topography become higher. We can see it in Matur, padangpanjang, Kototabang. The amount of Rainfall much lower in Biaro which located in east part of mountain. Tiku which located in the coastline got less rain than others area that located in higher place. The rainfall in this area which located in west part and slope of mountain (Sicincin) get much rain than the others. Rainfall amount in higher place (Sicincin, Padangpanjang, Kototabang, Matur) was bigger than area which located in lower altitude (Tiku, Biaro, Tanjungpati). This condition also similar if we compare with climatology rainfall as show in Fig.10.

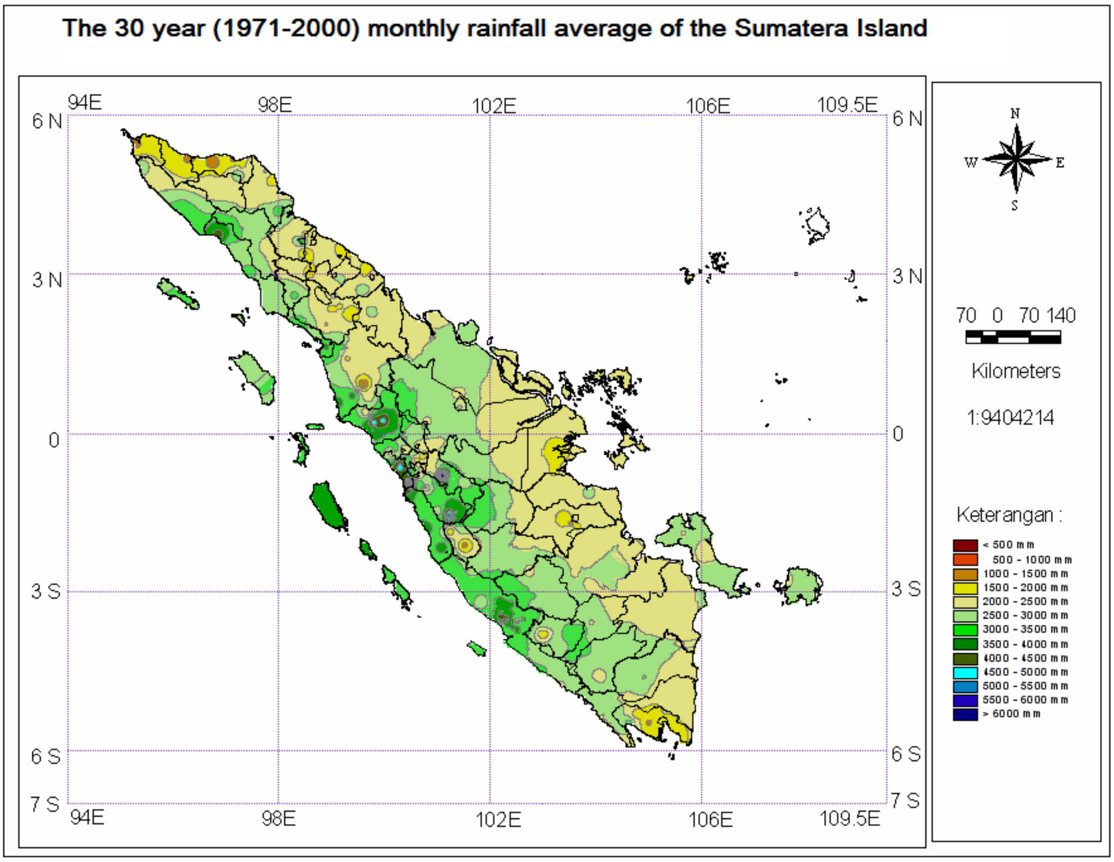

Figure 10. Rainfall distribution of Sumatera Island (1971-2000)

The surface wind data shows in tabel 1, mainly surface wind in Sicincin comes from the southwest, with percentage is 83.33%. Wind also comes from East and South-East with the same percentage is 8.33%. Previous explanation, said that Sicincin has much rain in 2005 years. It might cause by see breeze cloud move from the sea to the land, and saturated to be rain in higher place. The table also shows that surface wind in Padangpanjang. In this area surface wind mainly comes from the west, with percentage is 83.33%. Less rainfall occured in Padangpanjang in 2005. It might that rain already drop in Sicincin and just small amount of rain can reach Padangpanjang. We can say that, because surface wind in Padangpanjang move from the west which is same direction of Sicincin. In Kototabang we found that surface wind mainly comes from southeast with percentage is 69.53%. Wind also comes from East, South and Southwest, and the surface wind in Biaro mainly comes from the west with percentage is 33.87%. In this area wind comes from many direction

Table 1.Wind direction at Sumater Island

Wind Direction	Accumulation (%)			
	Sicincin	Pd. Panjang	Koto Tabang	Biaro
N	0.00	0.00	0.00	0.00
N-E	0.00	0.00	0.00	0.00
E	8.33	8.33	6.51	12.75
S-E	8.33	8.33	69.53	17.25
S	0.00	0.00	23.67	13.42
S-W	83.33	O	0.29	22.36
W	0.00	83.33	0.00	33.87
N-W	0.00	0.00	0.00	0.00