

# 第9回：特定地域の水文学Ⅰ

## モンスーンアジアの水文地域



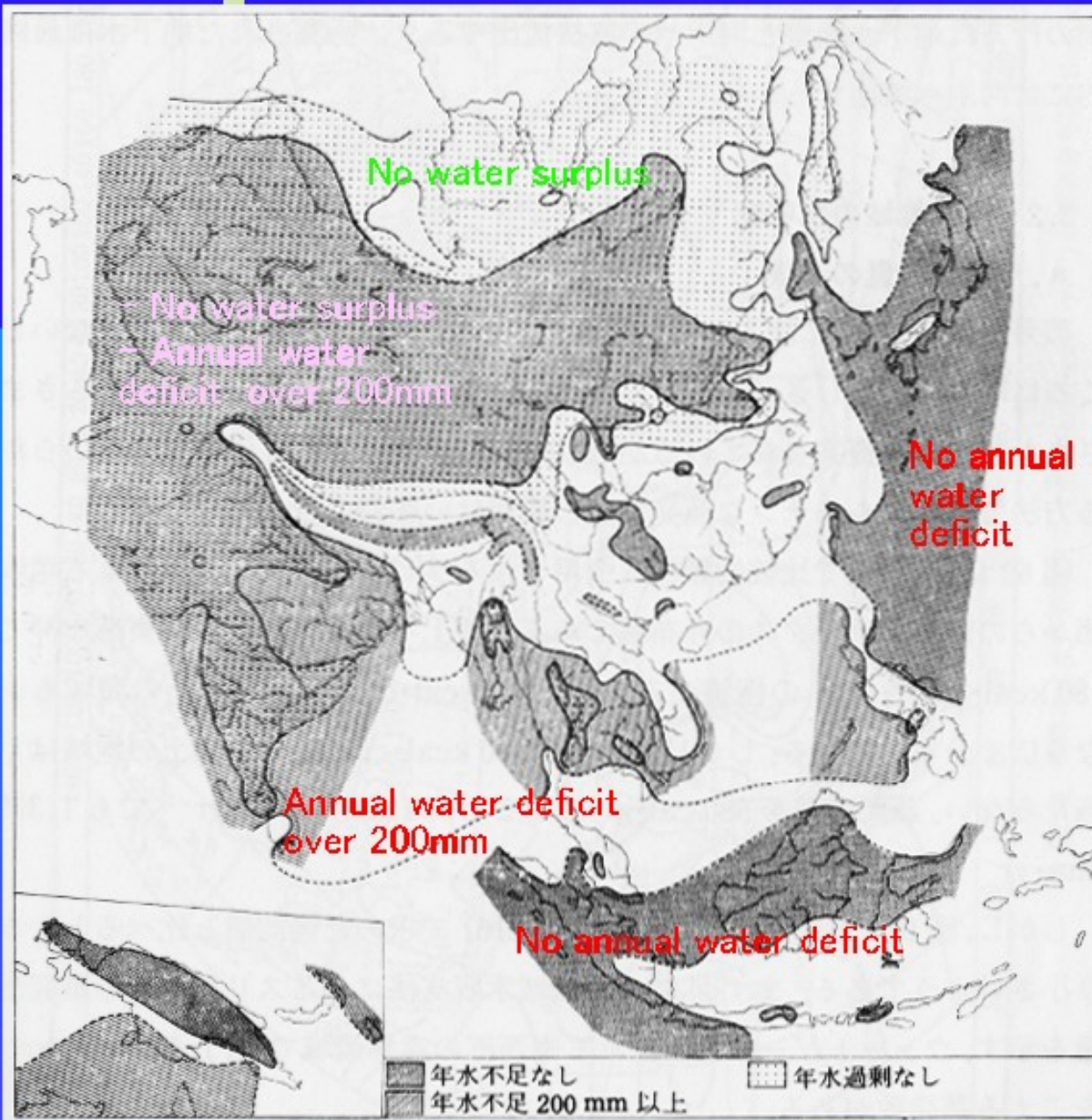
近藤昭彦@環境リモートセンシング研究センター

# 梶根(1972)の マップ

水収支とその季節性  
に基づいたモンスーン  
アジアの水文地域

1500箇所を超える観  
測データからソーンス  
ウエイトのブックキー  
ピング法で求めた水  
収支に基づく区分

try to revise with  
new datasets





# ソーンズウェイトの気候学的水収支

表 23 カリフォルニア州バークレーとニュージャージー州シーブルックの水収支計算  
(単位: mm)

	1月	2月	3月	4月	5月	6月	7月	8月	9月	10月	11月	12月	年
〔バークレー(カリフォルニア州)〕													
可能蒸発散量	26	32	45	56	71	84	88	82	75	63	43	28	693
降水量	130	112	94	37	24	5	1	1	13	31	62	106	616
差	104	80	49	-19	-47	-79	-87	-81	-62	-32	19	78	-77
貯留量変化	104	22	0	-19	-41	-56	-47	-33	-19	-8	19	78	
土湿貯留	278	300	300	281	240	184	137	104	85	77	96	174	
実蒸発散量	26	32	45	56	65	61	48	34	32	39	43	28	509
土湿不足	0	0	0	0	6	23	40	48	43	24	0	0	184
土湿過剰	0	58	49	0	0	0	0	0	0	0	0	0	107
流出量*	0	29	39	19	10	5	3	1	1	0	0	0	107
土湿保留	278	329	339	300	250	189	140	105	86	77	96	174	
〔シーブルック(ニュージャージー州)〕													
可能蒸発散量	1	2	16	46	92	131	154	136	97	53	19	3	750
降水量	87	93	102	88	92	91	112	113	82	85	70	93	1,108
差	86	91	86	42	0	-40	-42	-23	-15	32	51	90	358
貯留量変化	0	0	0	0	0	-38	-35	-17	-10	32	51	17	
土湿貯留	300	300	300	300	300	262	227	210	200	232	283	300	
実蒸発散量	1	2	16	46	92	129	147	130	92	53	19	3	730
土湿不足	0	0	0	0	0	2	7	6	5	0	0	0	20
土湿過剰	86	91	86	42	0	0	0	0	0	0	0	73	378
流出量*	61	76	81	61	31	15	8	4	2	1	1	37	378
土湿保留	361	376	381	361	331	277	235	214	202	233	284	337	

\* いずれの月も流出に利用できる水のうち、50%が翌月に繰りこされると仮定する。

$$E_t = 1.6 \left( \frac{10T}{I} \right)^a$$

$$I = \sum_{i=1}^{12} \left( \frac{T_i}{5} \right)^{1.514}$$

$$a = (492,390 + 17,920 I - 77.1 I^2 + 0.675 I^3) \times 10^{-6}$$

## Bookkeeping法

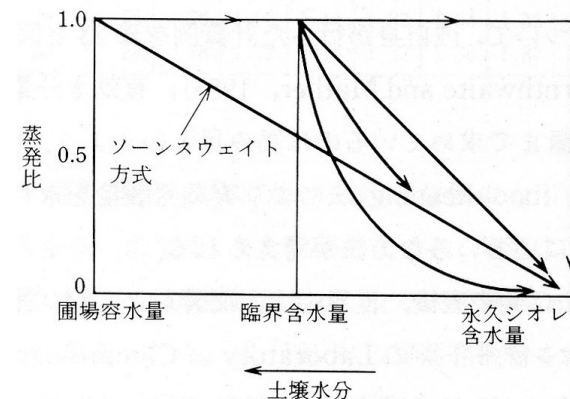
● 有効水分量を300mm

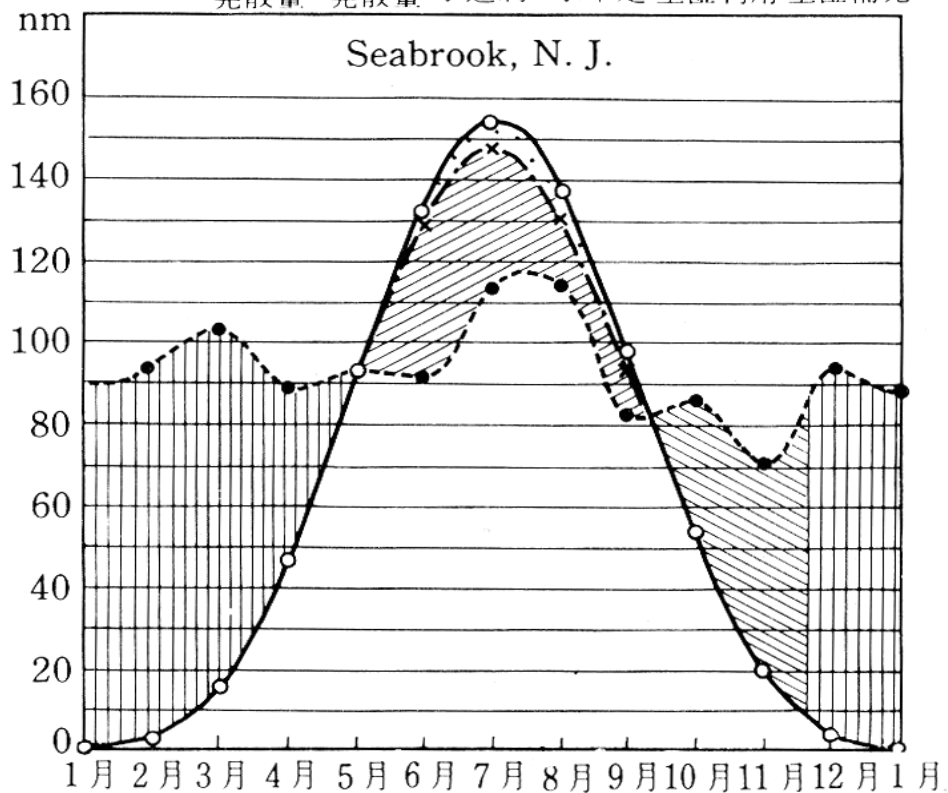
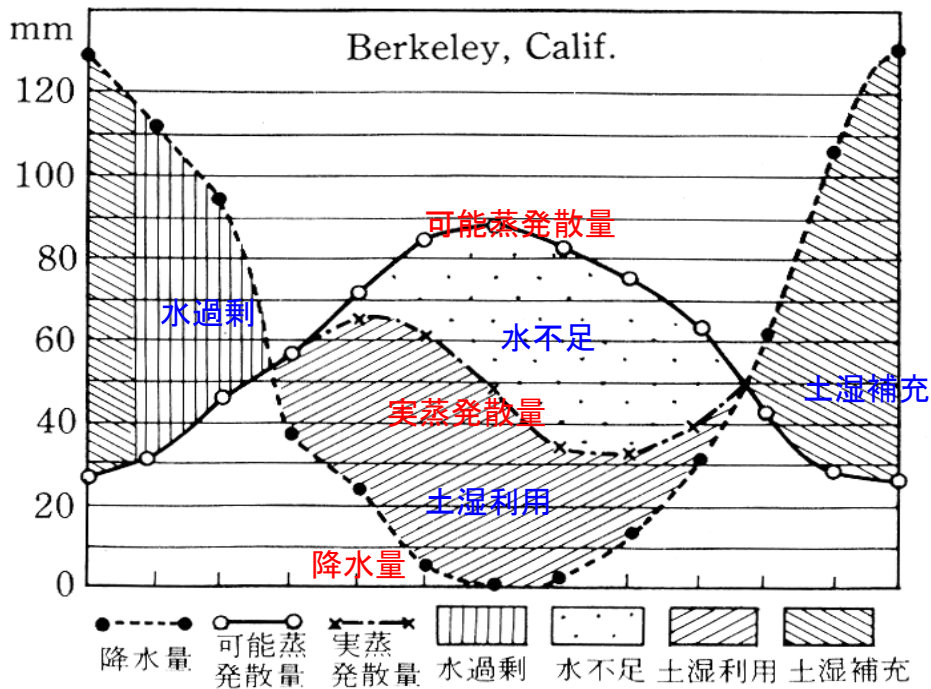
● 蒸発散量計算Et

● 次式から実蒸発散量を求める

$$\text{実蒸発散量} = \text{可能蒸発散量} \times \left( \frac{\text{有効水分の残量}}{\text{有効水分量}} \right)$$

(Thorntwaite and Mather, 1955)



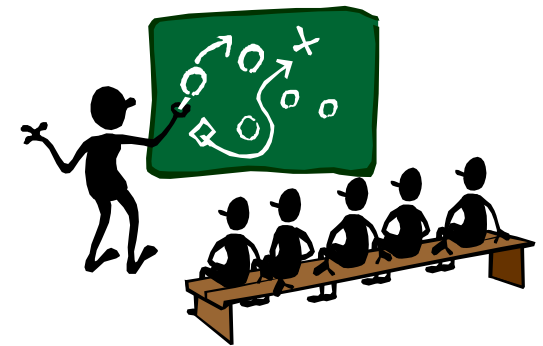


● Thornthwaiteの夢  
「世界の気候区分」

● 1963年没

● その後、Legates and Mather(1992) によって実現

たしかに、Bookkeeping法は  
ブラックボックス的なモデルだが  
その中に、現象の本質的な要素  
が含まれている  
— 汚い水でも皿を洗っている内に —  
— 徐々にきれいになる —



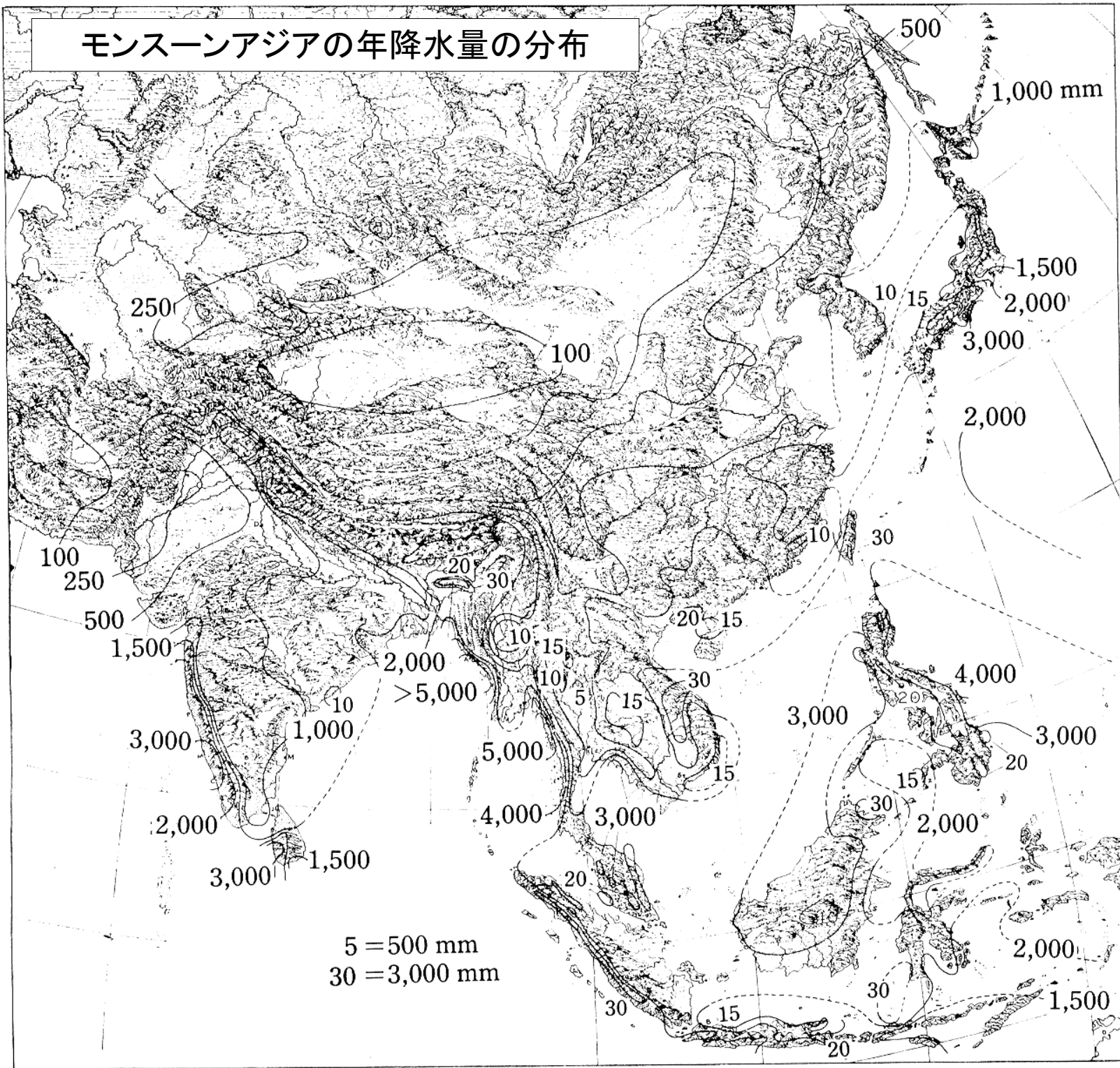
(榎根勇、「水と気象」、朝倉書店)



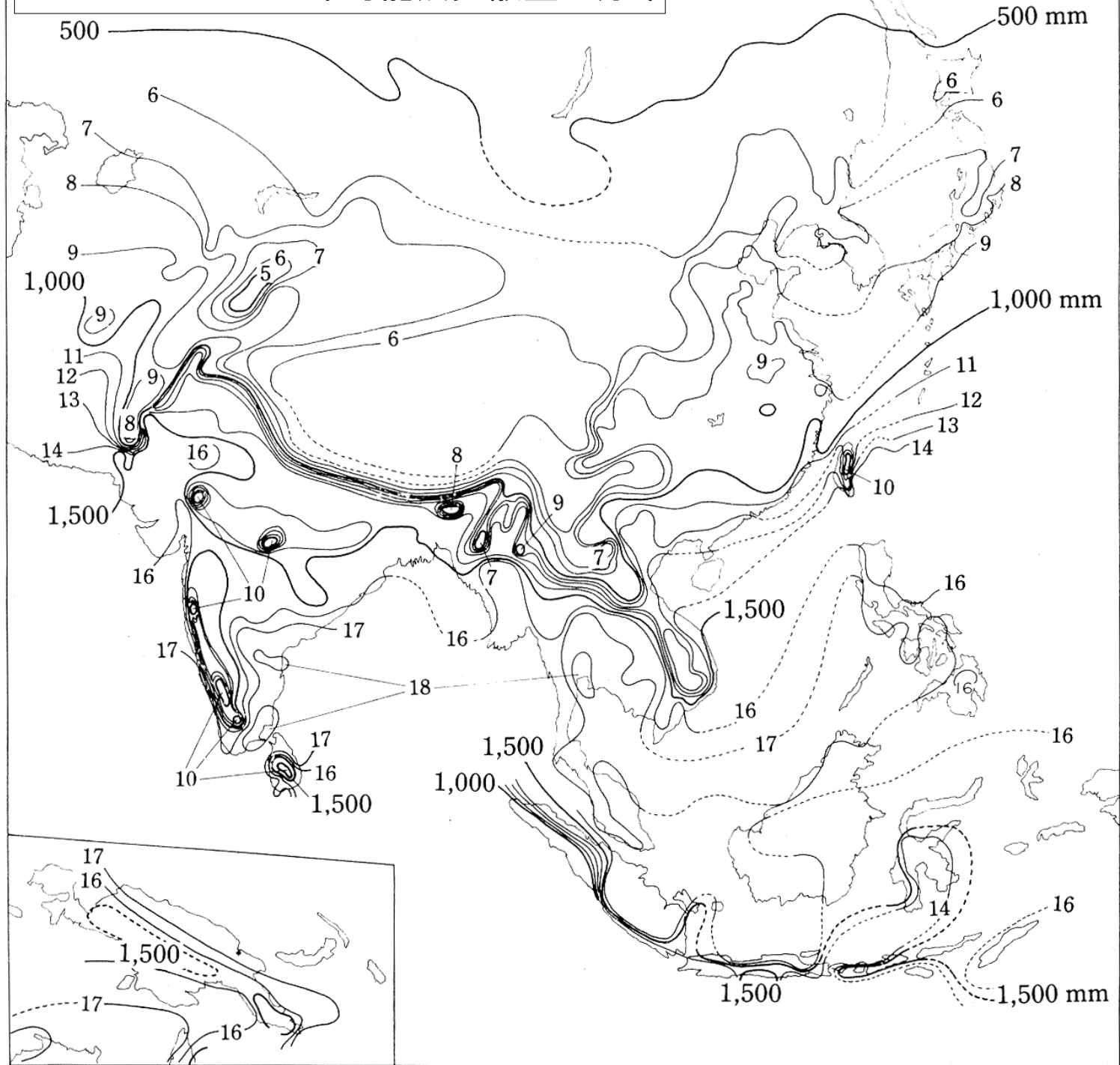


アジアの降水量分布の特徴を読み取れるか

# モンスーンアジアの年降水量の分布



# モンスーンアジアの年可能蒸発散量の分布



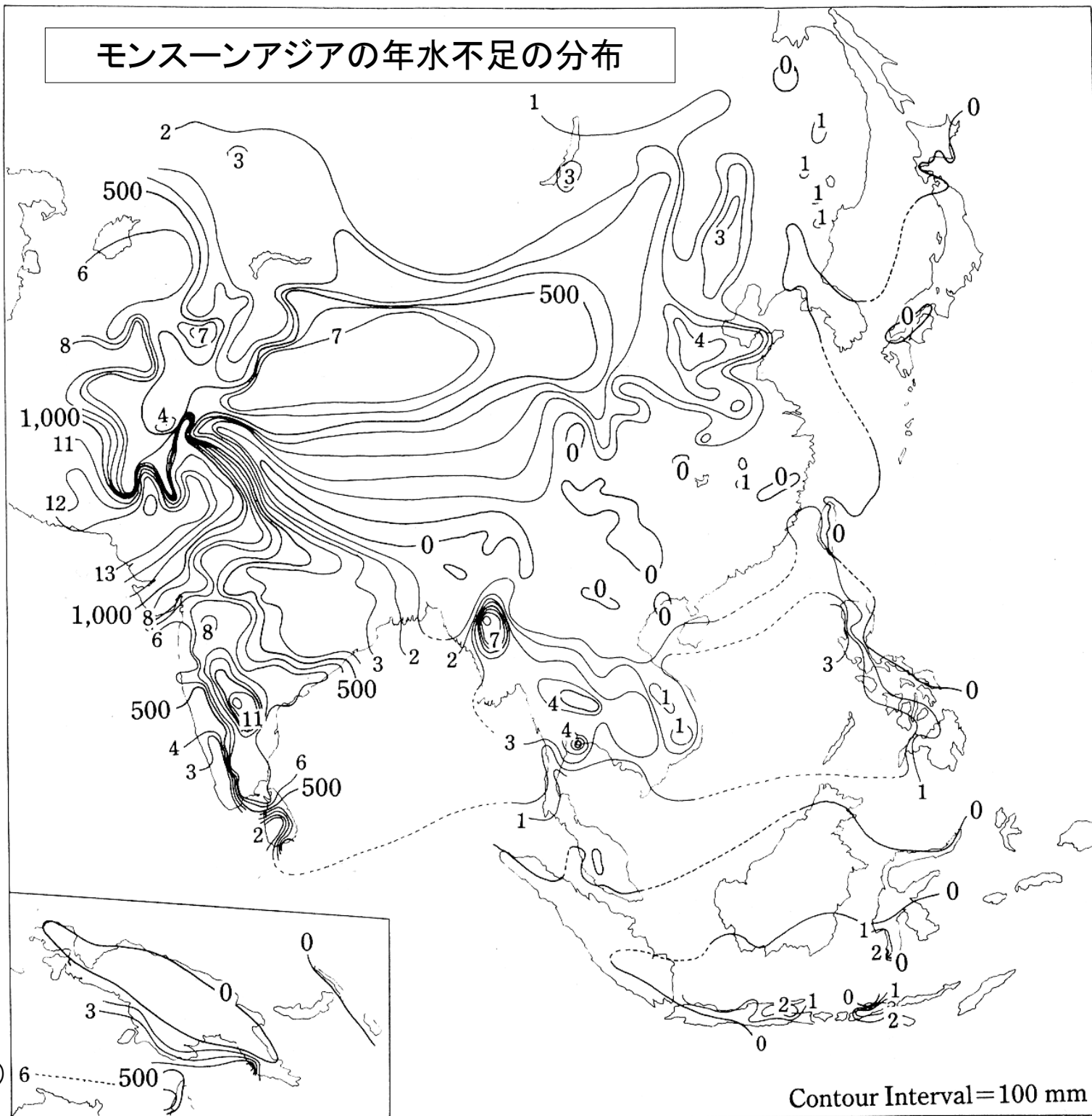
(梶根、1972)





雨季と乾季があるモンスーン地域では  
どうなっているか？

# モンスーンアジアの年水不足の分布



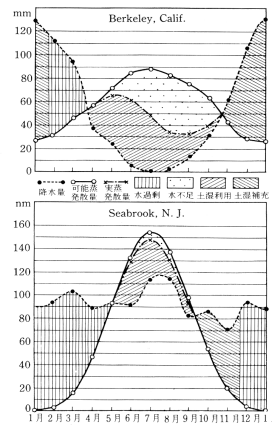
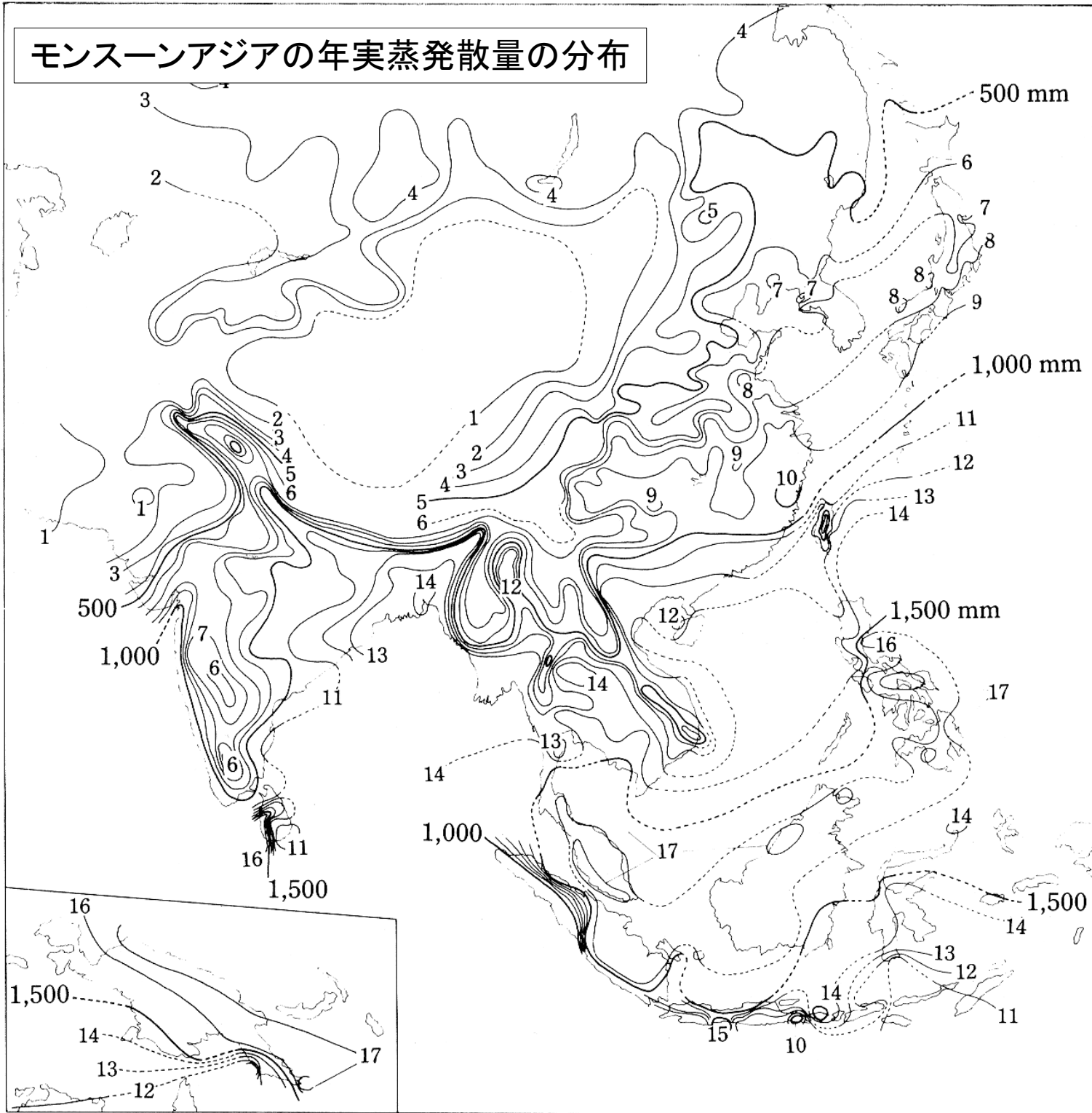
(榎根、1972)

Contour Interval=100 mm



土壤水分不足による蒸発抑制を考慮

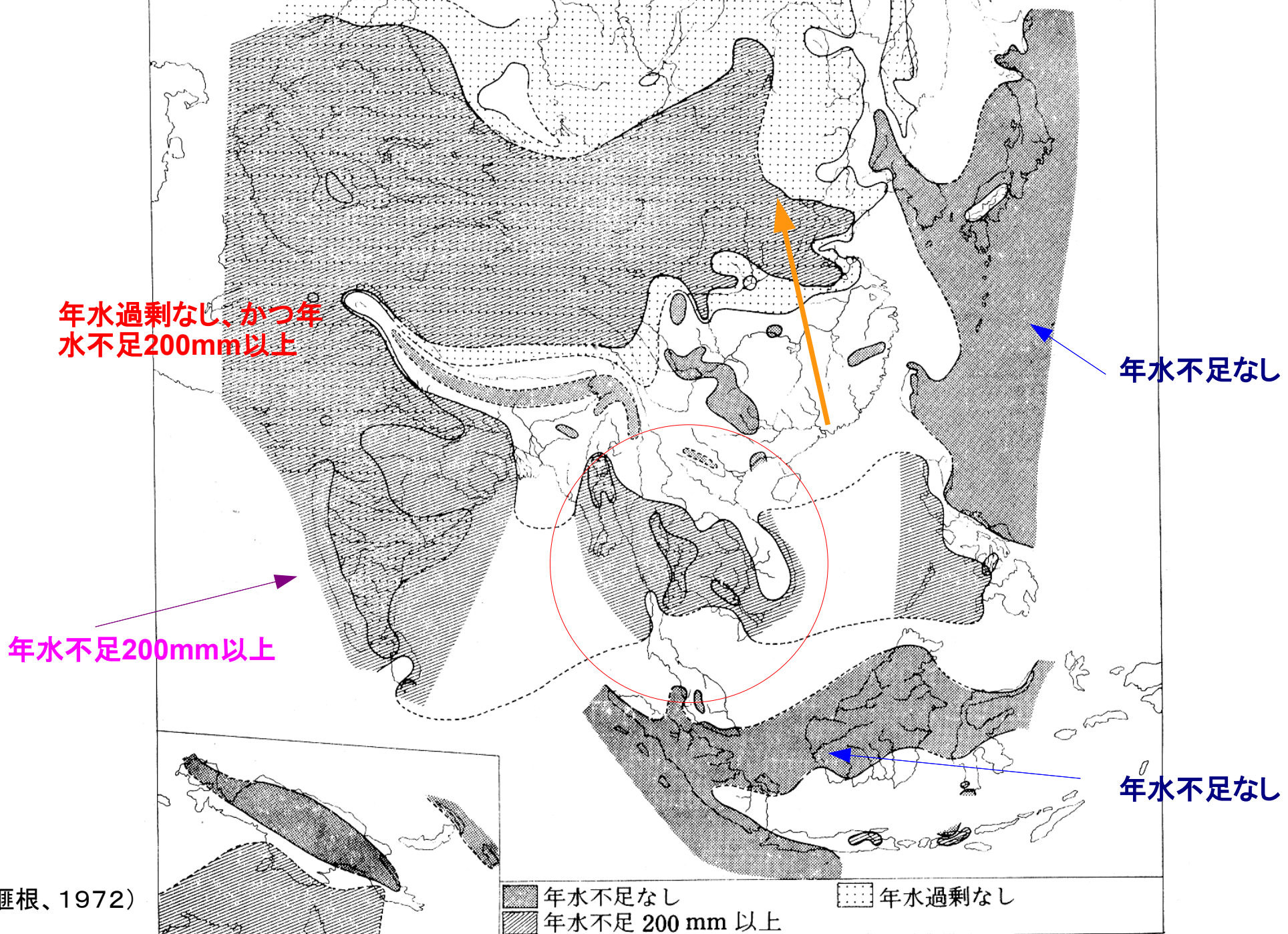
# モンスーンアジアの年実蒸発散量の分布



(榎根、1972)



# モンスーンアジアの地域区分



(梶根、1972)

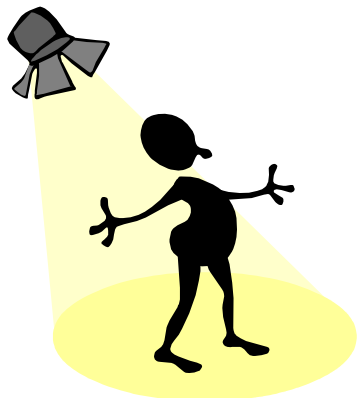
## なぜ年水不足200mmを重視したか

○河川の基底流量から推定した日本の地下水涵養量は約400mm/年  
(約1mm/日程度)

○モンスーン地域では雨季と乾季がある  
→雨季、乾季を6ヶ月とすると年地下水涵養量は200mm

年間に水過剰があれば、それらの地域では200mmを限度として、河川の流量を減少させることを前提に地下水を利用できる

水過剰の行方は地下水涵養と河川への直接流出であり、涵養された地下水は河川へ流出するから



## なぜ地域区分が重要か

古典的な研究を新しいデータで





新しいデータセットが  
どんどん登場!

# New datasets

- 何が新しいか?
- グリッドベース、空間分解能は0.5度
  - 熱収支に基づく蒸発散量計算
  - 複数の空間属性の取り込みが可能

Datasets open for the public through internet or CD-ROM are used to calculate water budget. (1) to (5) are included in the Global Ecosystem Databases(GEDB) provided by EPA-NOAA/NGDC. (6) is on-line database provided by UNEP/GRID(<http://www.grid.unep.ch/>)

- (1) Precipitation: ➤ Leemans and Cramer IIASA mean monthly precipitation  
Legate and Willmott Monthly Average Precipitation
- (2) Air temperature: ➤ Leemans and Cramer IIASA monthly surface air temperature  
Legate and Willmott Monthly Average Air Temperature
- (3) Sunshine duration: Leemans and Cramer IIASA average month cloudiness
- (4) Albedo : Matthews seasonal albedo
- (5) Altitude : ETOPO30
- (6) Soil moisture storage capacity: Bouwman soil water holding capacity
- (7) TRIP : Total Runoff Integrating Pathways

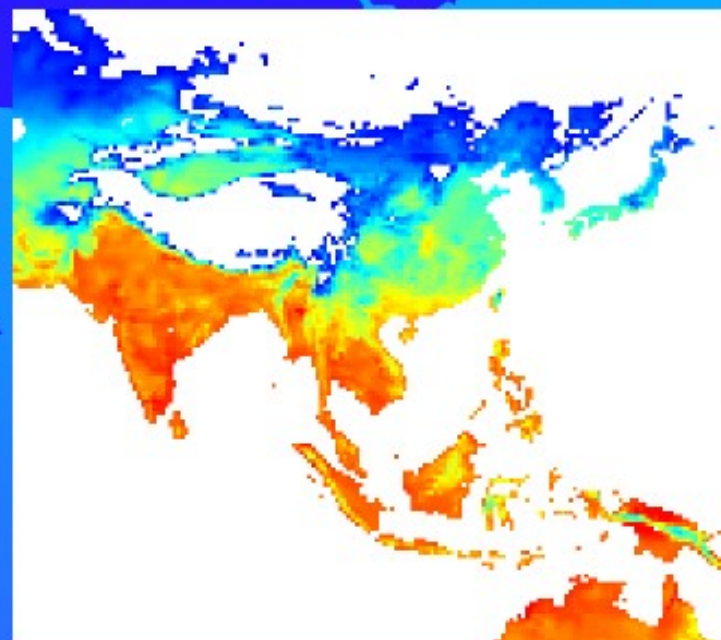
(Kondoh *et al.*, 2004)

## Annual Air Temperature in Monsoon Asia

Leemans and Cramer IIASA monthly surface air temperature



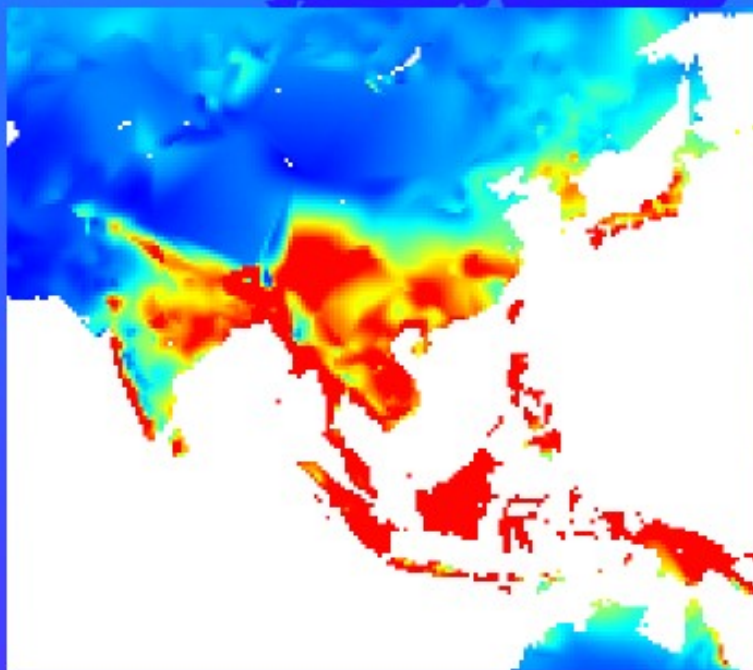
## Example of input data



## Annual Precipitation in Monsoon Asia

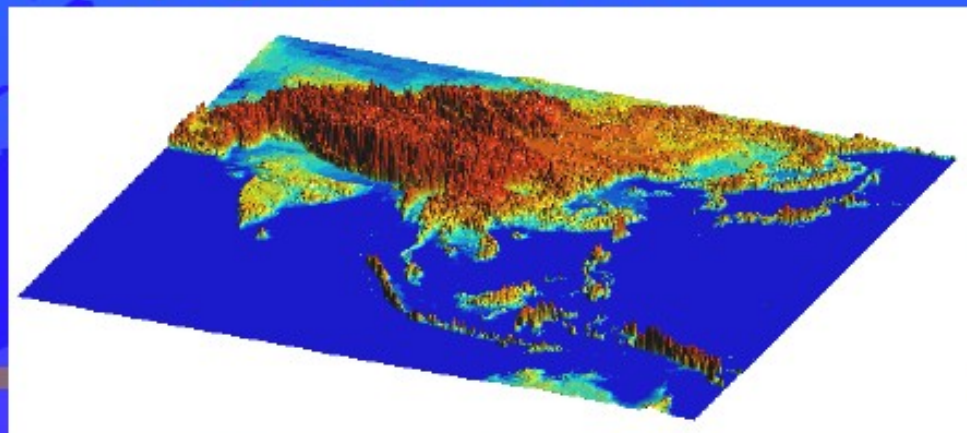
Leemans and Cramer IIASA mean monthly precipitation

mm/year  
2000



0

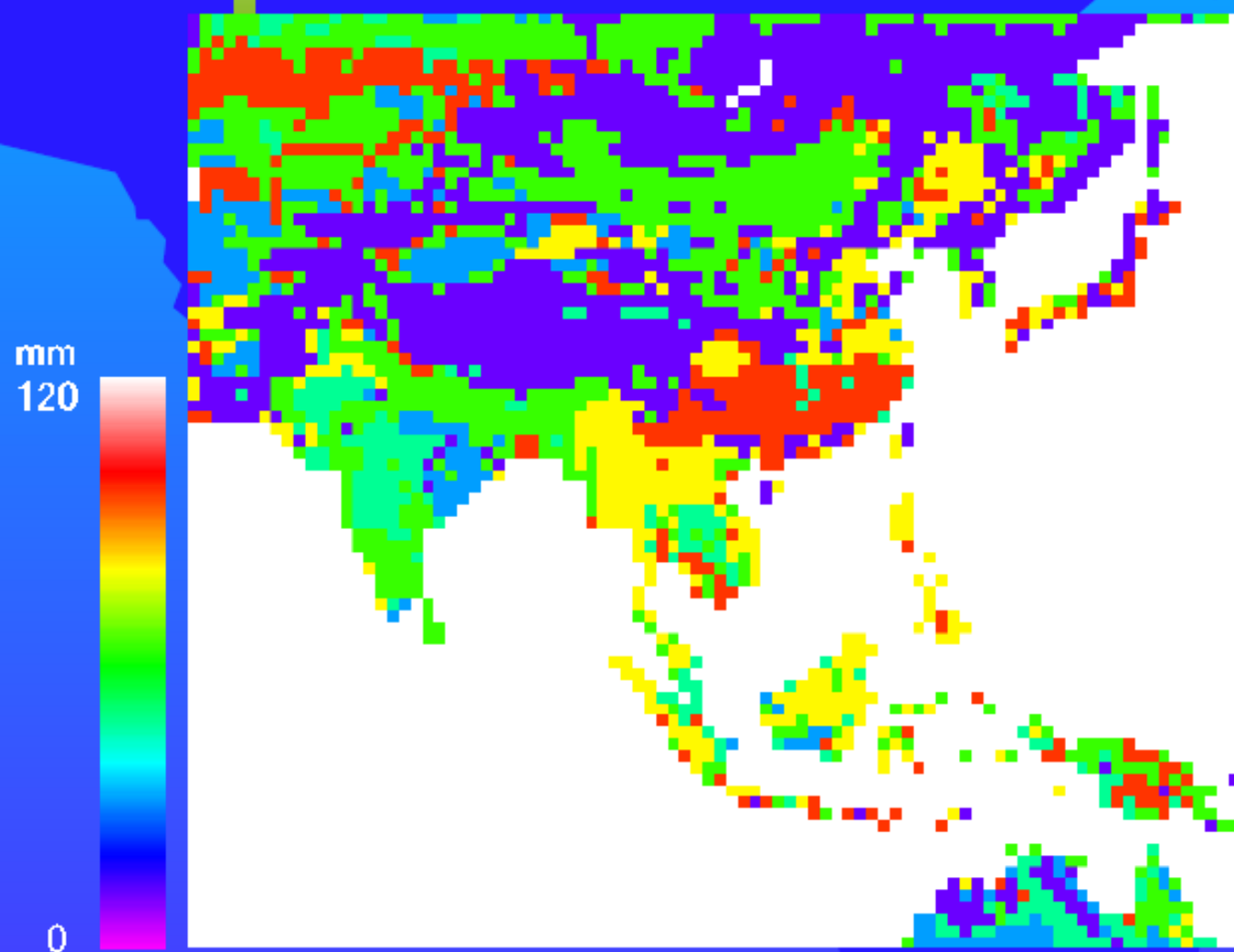
## Topography ETOPO30



新しいデータセットはホームページ[リンク]で紹介中



# 土壤水分貯留容量



Distribution of soil water holding capacity, at field capacity for the top **30 cm** of soil only. It was derived from information on soil type and texture compiled by L. Zabler(1986).

Thornthwaite initially assumed soil moisture storage capacity as **100mm** in his book keeping method, but later revised it to **300mm**.

Field evidences show the depth concerning short time water circulation is about one meter. It is three times larger than 30cm, and maximum SHC of 120mm is about 1/3 of 300mm.

So, the value multiplied by three is considered to be appropriate for the Soil Moisture Storage Capacity in the water budget calculation.

**SWHC values multiplied by three are used for the calculation.**

# Method to calculate potential evaporation

$$E_p = \alpha \times \frac{\Delta}{\Delta + \gamma} R_n$$

Priestly & Taylorの可能蒸発量

where,  $E_p$ : potential evaporation(mm),  $R_n$ : net radiation(mm),  $G$ : soil heat flux(mm),  $\Delta$ : slope in saturated vapor curve,  $\gamma$ : psychrometric constant,  $\alpha$ : Priestley and Taylor constant(=1.26).

$$R_n = (1-r)R_s - 1.11(0.2 + 0.8n/N)(100-T)$$

where,  $r$ : albedo,  $R_s$ : solar radiation,  $n/N$ : fraction of sunshine duration,  $T$ : air temperature. As for solar radiation following equations are used:

$$R_s = (a + b \times n/N) \times R_e$$

$$a = 0.29 \cos(\Phi)$$

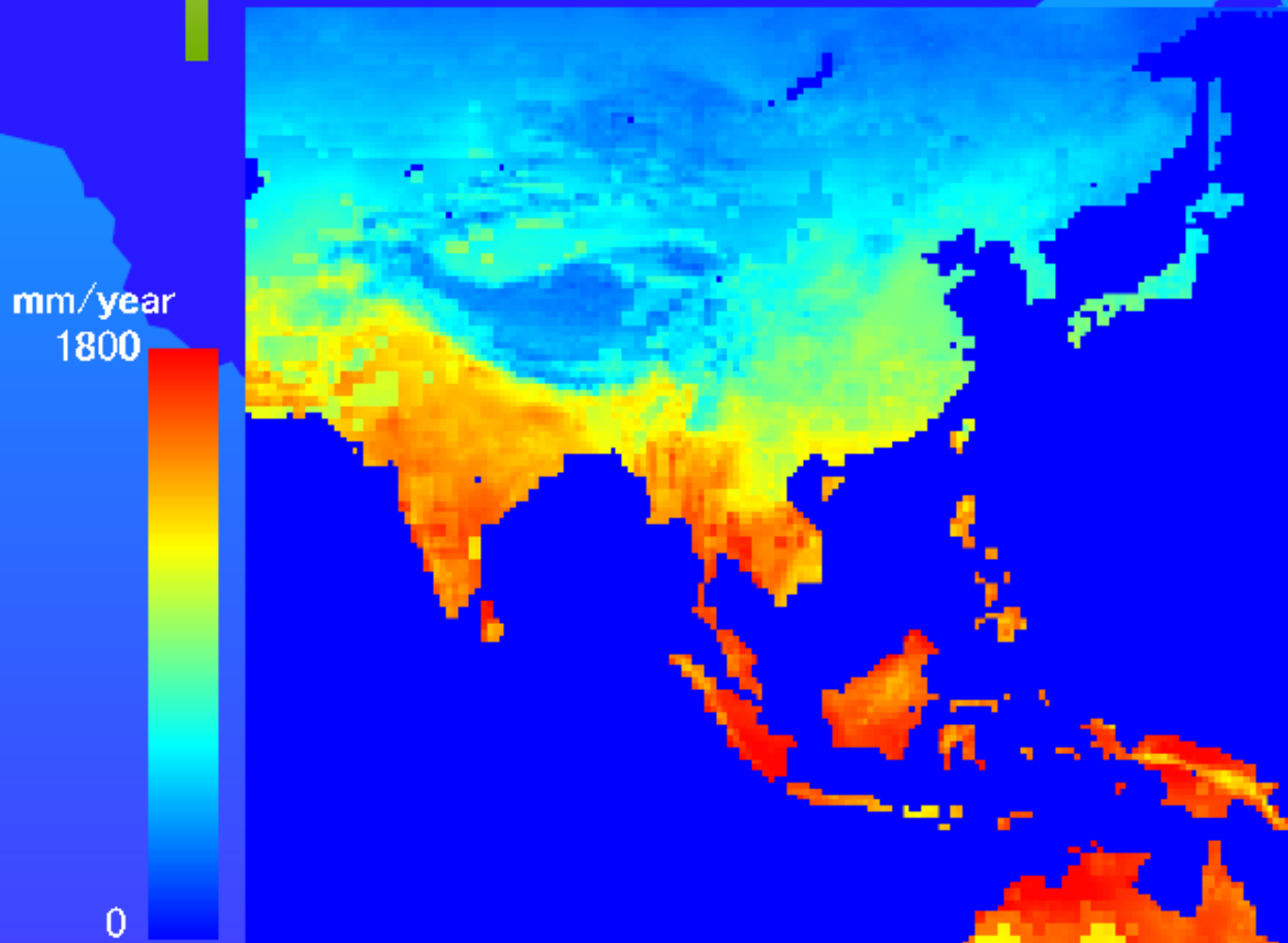
$$b = 0.71 - 0.29 \cos(\Phi)$$

技巧に走るではないぞ

where  $R_e$ : extra terrestrial radiation,  $\Phi$ : latitude, and  $R_e$  can be calculated using latitude and time.



# Distribution of potential evaporation in Monsoon Asia



Potential evaporation by Priestley and Taylor is the one expected in extensive wet area with no advection.

When there is no water to be evaporated, evaporation is controlled by water availability. It is not actual evapotranspiration, however, it is useful in the irrigation management.

# Method to calculate Water Budget

## Actual Evapotranspiration

```
if  $P_i < E_{pi}$   
   $E_{ai} = P_i - (S_{mi} - S_{mi-1})$   
else  
   $E_{ai} = E_{pi}$ 
```

where P: precipitation,  $E_p$ : potential evapotranspiration,  $E_a$ : actual evapotranspiration,  $S_m$ : soil water storage in a month, i denotes month.

## Soil water storage (by Donker(1987))

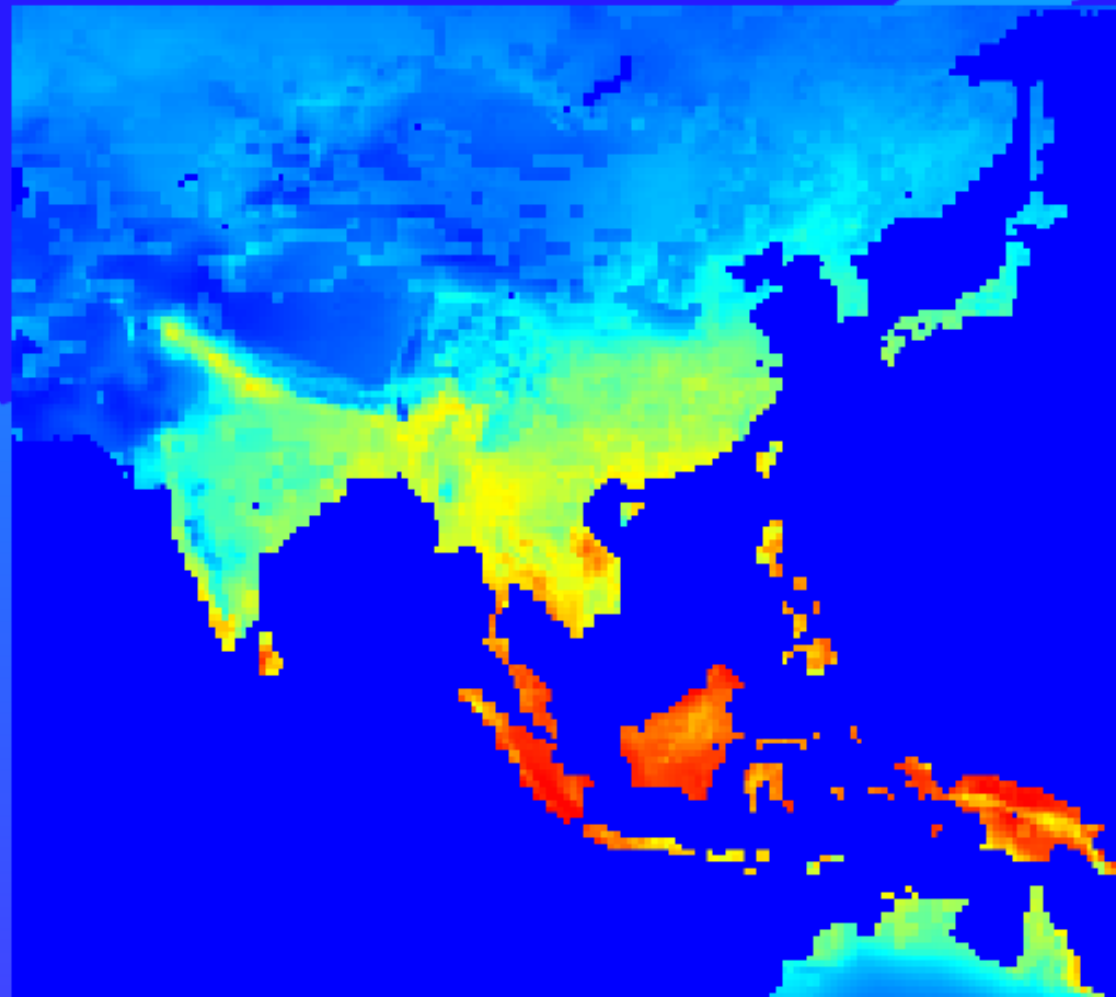
```
if  $P_i < E_{pi}$   
   $AWL_i = AWL_{i-1} + E_{pi} - P_i$   
   $S_{mi} = W_c \exp(-AWL_i / W_c)$   
else  
   $S_{mi} = S_{mi-1} + (P_i - E_{pi})$ 
```

where AWL: accumulated potential water loss,  $W_c$ : soil water storage capacity.

## Water deficit and surplus (by Legates and Mather(1992))

```
if  $S_{mi} > W_c$   
   $S_i = P_i - E_{ai} - (S_{mi} - S_{mi-1})$   
   $D_i = 0$   
else  
   $S_i = 0$   
   $D_i = E_{pi} - E_{ai}$ 
```

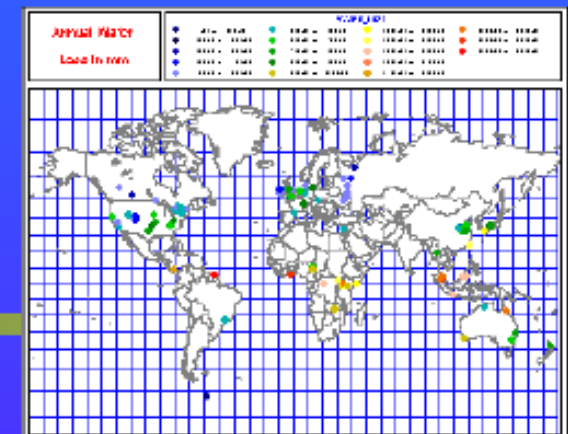
# Actual Evapotranspiration in Monsoon Asia



mm/year  
1800

C

- Evapotranspiration in arid and semi-arid area is controlled by water availability
- Maximum evapotranspiration is around 1,800mm/year
- The distribution is appropriate compared with previous studies.





# 水文地域区分の基準

- Average baseflow is about 1mm/day in Japan.
- It leads to the annual total about 400mm

The region with more than 400mm water surplus is very water rich region.

- If half a year is wet period and the rest is dry period, 200mm of baseflow(=groundwater recharge) is expected.
- This value is a upper limit of water usage in this case.

WET

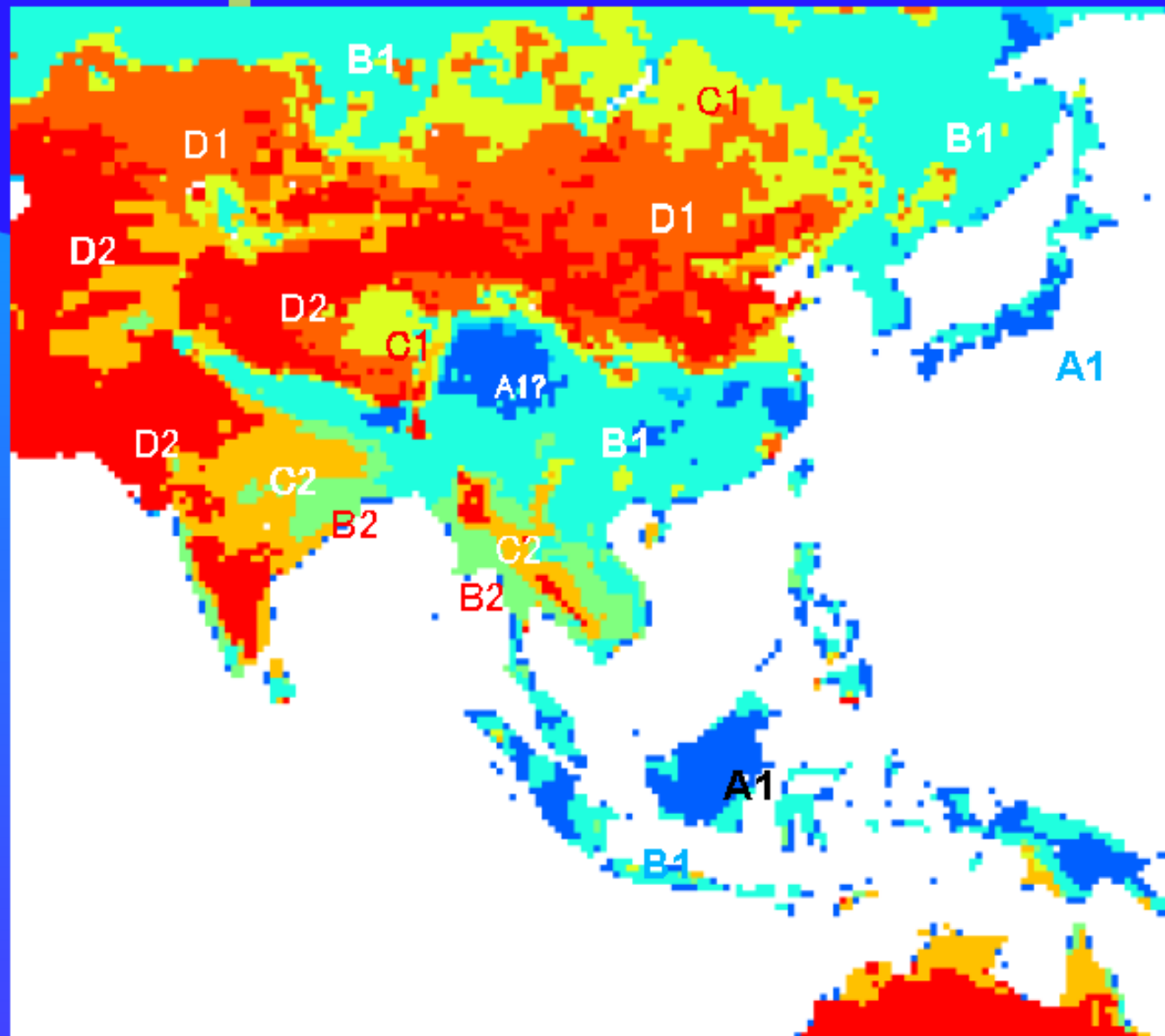


DRY

- Region A1: water surplus all year around(ATS>400mm);
- Region A2: water surplus all year around(ATS<400mm);
- Region B1: water surplus with some months deficit (ATD <200 mm);
- Region B2: water surplus with some months deficit (ATD >200 mm);
- Region C1: water deficit with some months surplus (ATD <200 mm);
- Region C2: water deficit with some months surplus (ATD >200 mm).
- Region D1: water deficit all year around (ATD <200 mm);
- Region D2: water deficit all year around (ATD >200 mm);

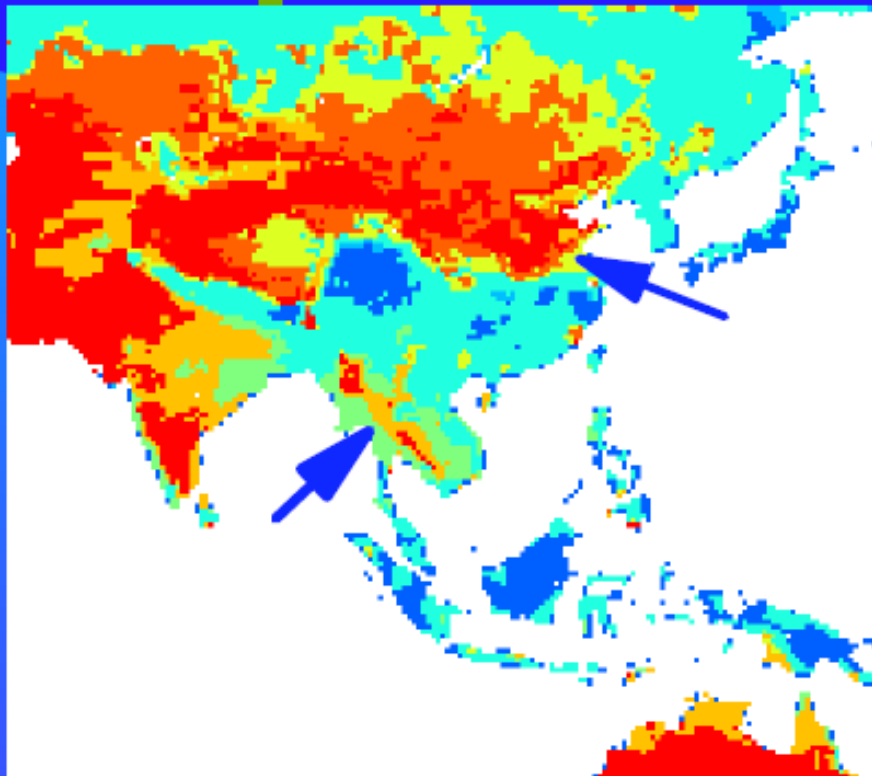
(ATD: Annual Total Deficit, ATS: Annual Total Surplus)

# Hydrological Region in Monsoon Asia



- **Region A1**: water surplus all year around(ATS>400mm);
- **Region A2**: water surplus all year around(ATS<400mm);
- **Region B1**: water surplus with some months deficit (ATD <200 mm);
- **Region B2**: water surplus with some months deficit (ATD >200 mm);
- **Region C1**: water deficit with some months surplus (ATD <200 mm);
- **Region C2**: water deficit with some months surplus (ATD >200 mm).
- **Region D1**: water deficit all year around (ATD <200 mm);
- **Region D2**: water deficit all year around (ATD >200 mm);

# 水文地域図から何を読み取るか？



## - 南水北調

A、B地域からD地域への水の輸送  
水問題の理解

## - 乾燥と湿潤の近接性

チャオプラヤ下流域

乾期稲作は大ダム建設後開始。一見年間を通して湿潤な雰囲気があるが、水不足問題は存在

地域性の理解

You may feel natural by looking the map, however, there is a possibility to collect experiences in the fields, and systematize the hydrological knowledge by using hydrological region as a base map.

Analyses by GIS



# モンスーンアジアの特徴は何だろうか

- 温暖、湿潤→洪水 Too much water issue!

ヨーロッパ系では乾燥地域の水文学が進み、水不足 Too little water issue が課題だったが

## [近藤私見]

- 湿潤と乾燥の近接性
- 乾燥地域の洪水問題も重要



水の豊富な地域の水不足問題→水汚染

# 水問題

- ・量的問題(水資源)
  - ・洪水
- 長期流出  
短期流出



長期流出は水収支である

- ・PUB Predictions in Ungauged Basins

水資源の量、季節的配分は予測可能



Data SIO, NOAA, U.S. Navy, NGA, GEBCO

© 2009 DMapas

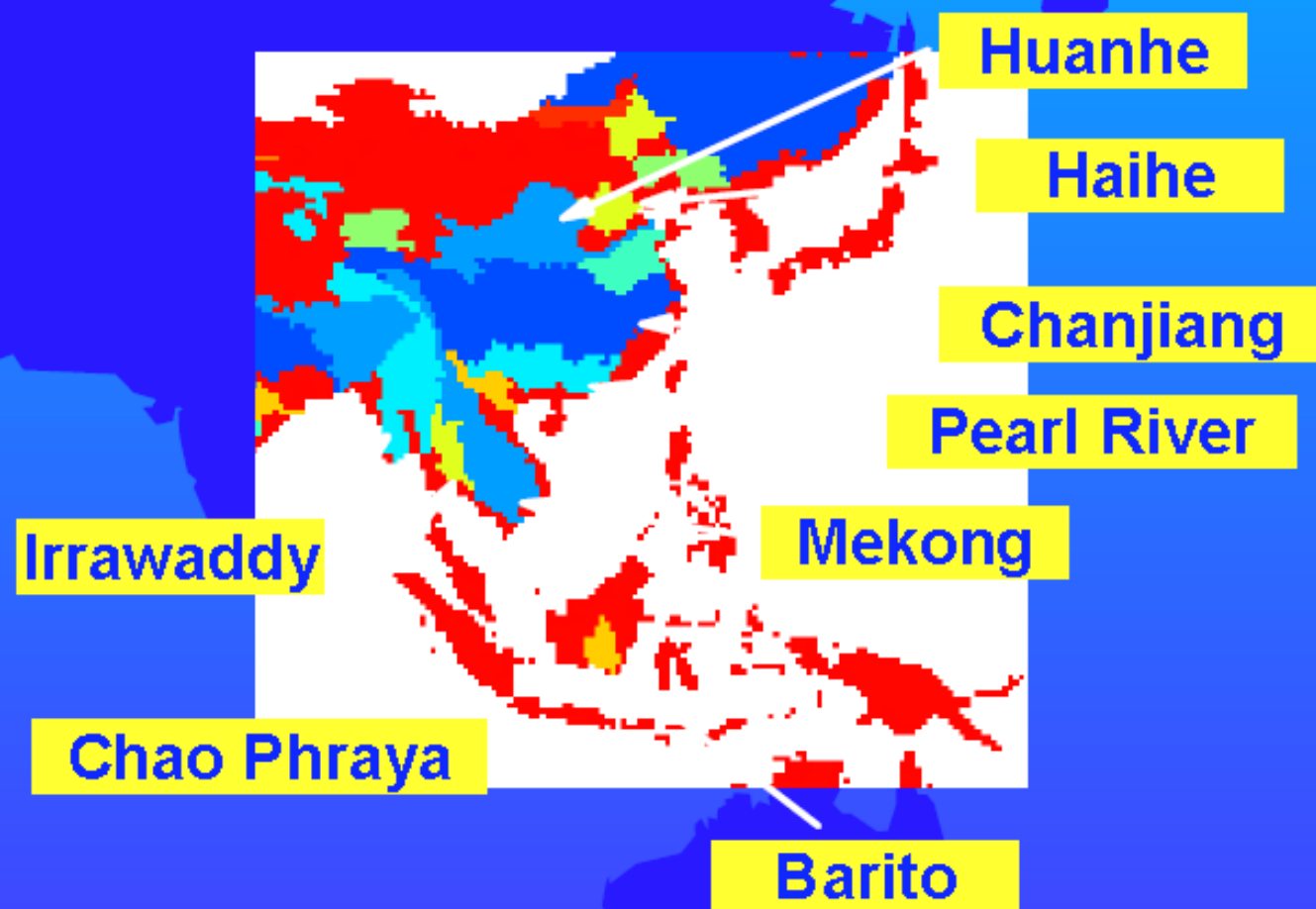
© 2009 Tele Atlas

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# Major River Basins

Data Source: TRIP Total Runoff Integrating Pathways



TRIP is available from  
<http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html>

# Areal fraction of hydrological region within the watershed and annual water budget

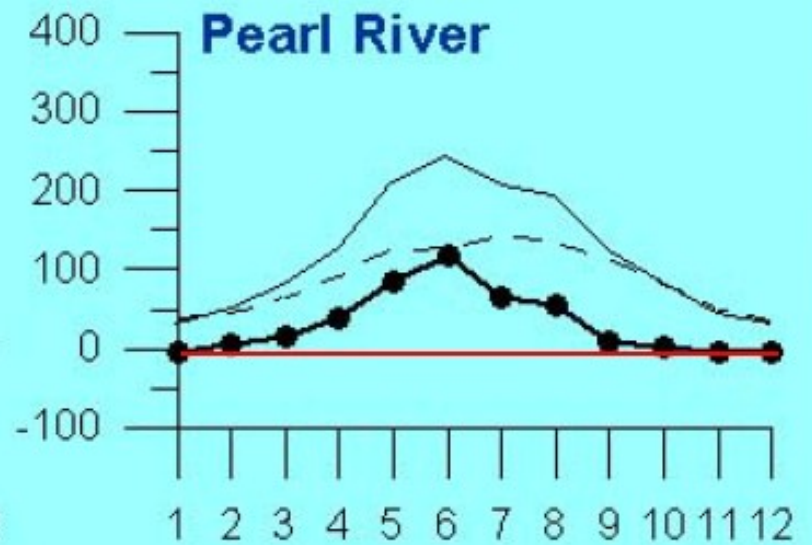
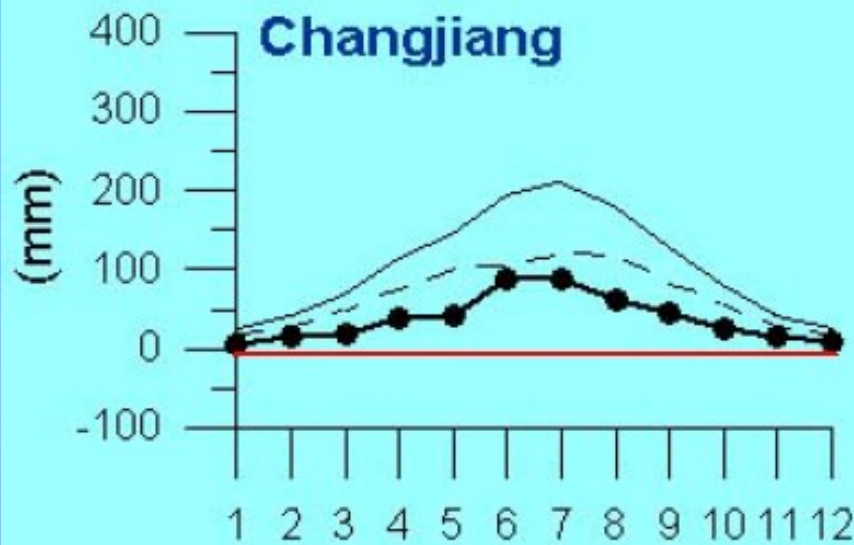
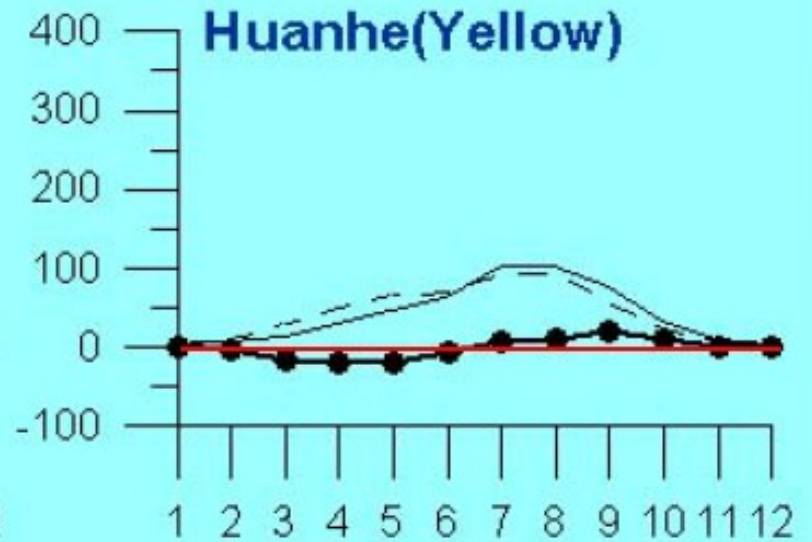
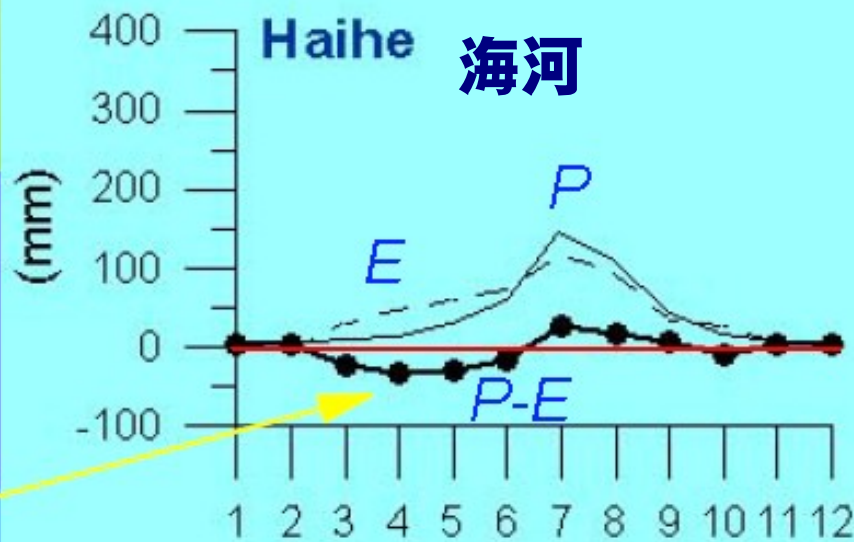
	A1	A2	B1	B2	C1	C2	D1	D2	P	E	P-E
Haihe	--	--	--	--	10.6	7.6	28.8	53.0	450	491.2	-41.2
Yellow River	5.7	0.6	9.7	--	10.3	1.1	28.8	43.9	492.3	502.7	-10.3
Chanjiang	19.8	1.6	61.3	0.7	10.9	0.7	4	0.9	1253.1	801.2	451.9
Pearl River	5.1	--	84.7	--	10.2	--	--	--	1425.8	1052	373.8
Mekong	12.2	--	32.3	34.4	---	18.3	--	2.9	1741.5	1075	666.5
Chao Phraya	--	--	5	28.3	---	58.3	--	8.3	1429.5	1180.5	249
Irrawaddy	6	0.4	35.3	23.7	5.3	14.7	6.4	8.3	1547.7	877.5	670.2
Barito	80	--	20	--	---	--	--	--	2805.9	1645.2	1160.7

- Large rivers flow through several different hydrological regions
- It forms characteristics of the long-term runoff characteristics

流域を点で捉えるか、面でとらえるか

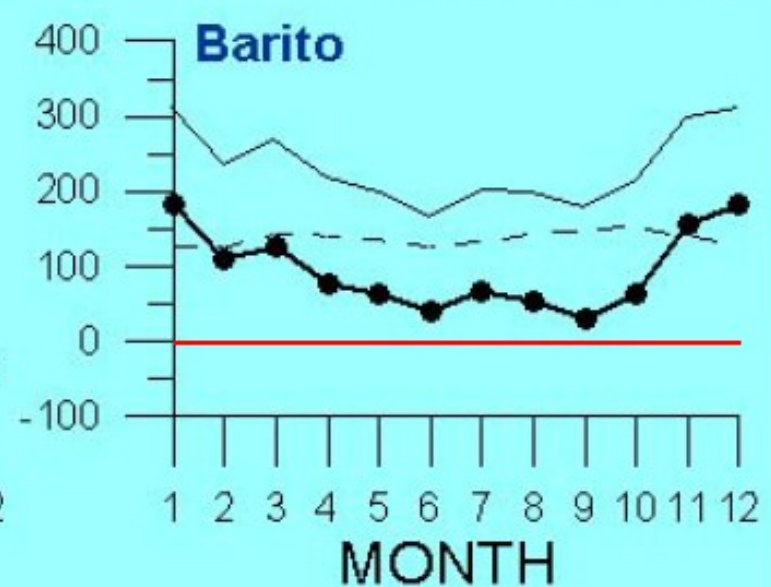
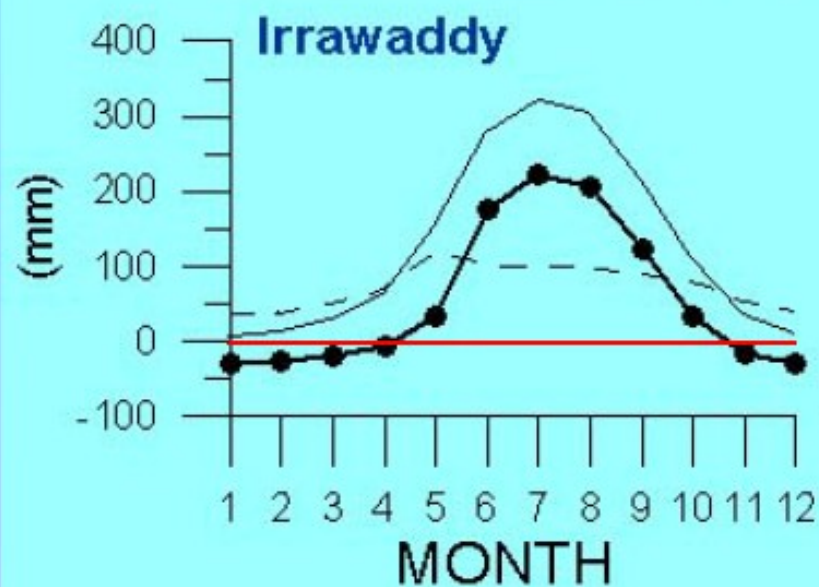
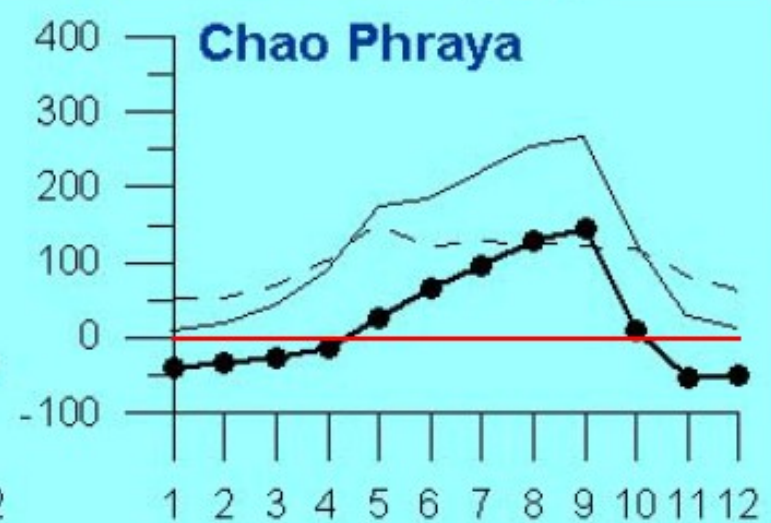
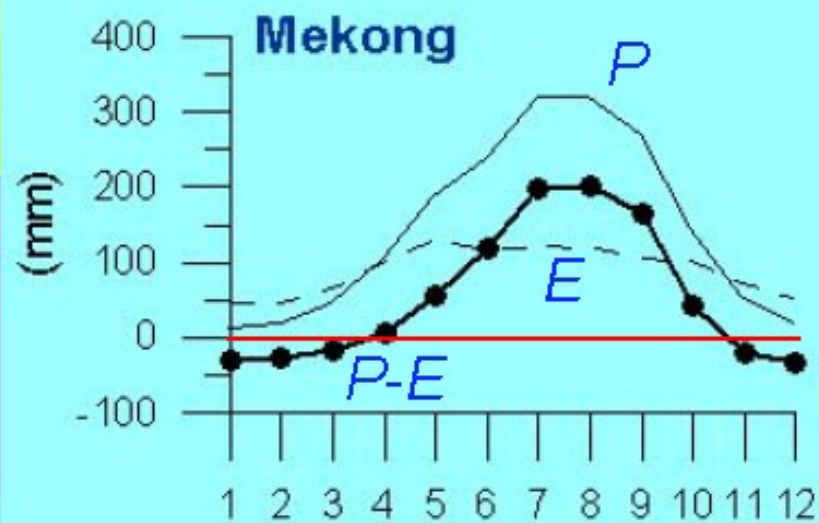
# Monthly Water Budget (1)

Minus water budget in spring causes heavy groundwater pumping



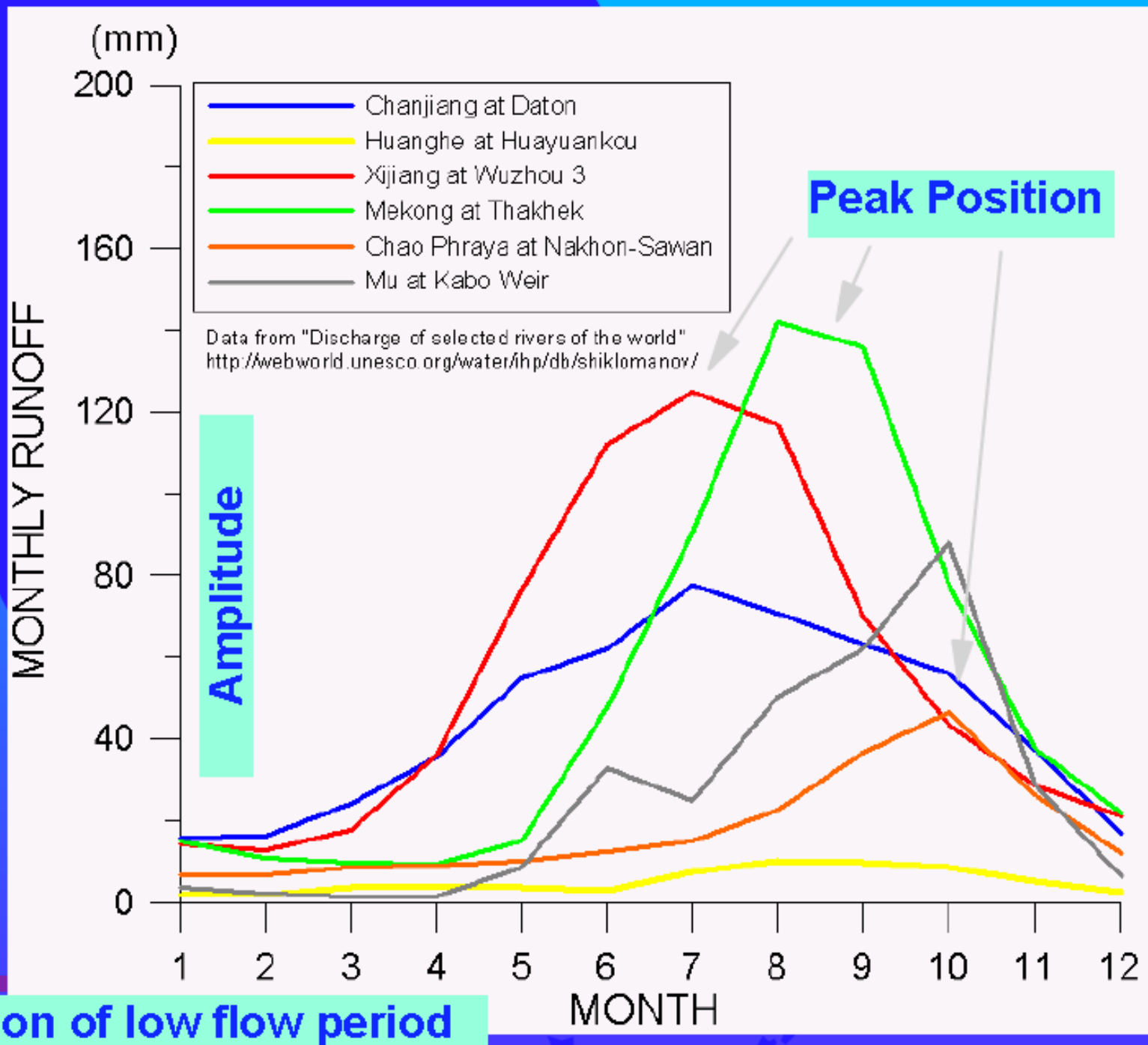


# Monthly Water Budget (2)



# How about the accuracy?

これは実測流量・・・水収支計算  
結果と比較してみよう



# Conclusions



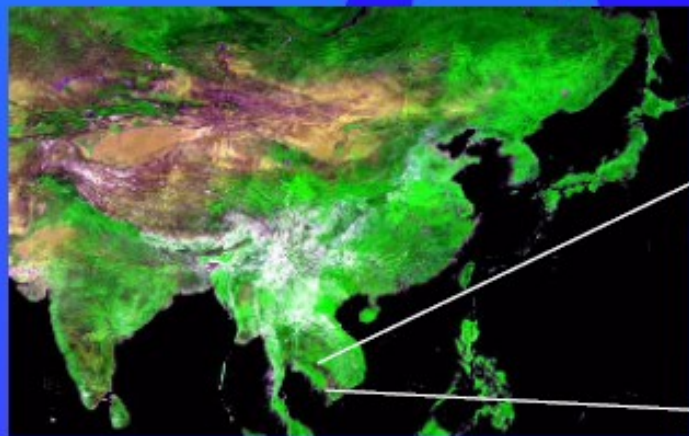
## 水文地域図

- 地域の水問題の理解、対策の提言に役立つとともに、地域の経験を蓄積する空間的フレームワークとなる



## 大河川の水収支特性

- 流域ごとの水収支の季節性の理解は適切な水資源管理の方法の策定に役立つ



- Continental scale
- Long term runoff

**Water budget**



- Basin scale
- Short term runoff

**Delay of runoff from P.**



# 蒸発散量の上限は？

Budykoによる年潜熱フラックス

蒸発の潜熱を500cal/gとすると80kcal/cm<sup>2</sup>/年=1379mm/年 →ちょっと少ない

(梶根勇、「水と気象」、朝倉書店)

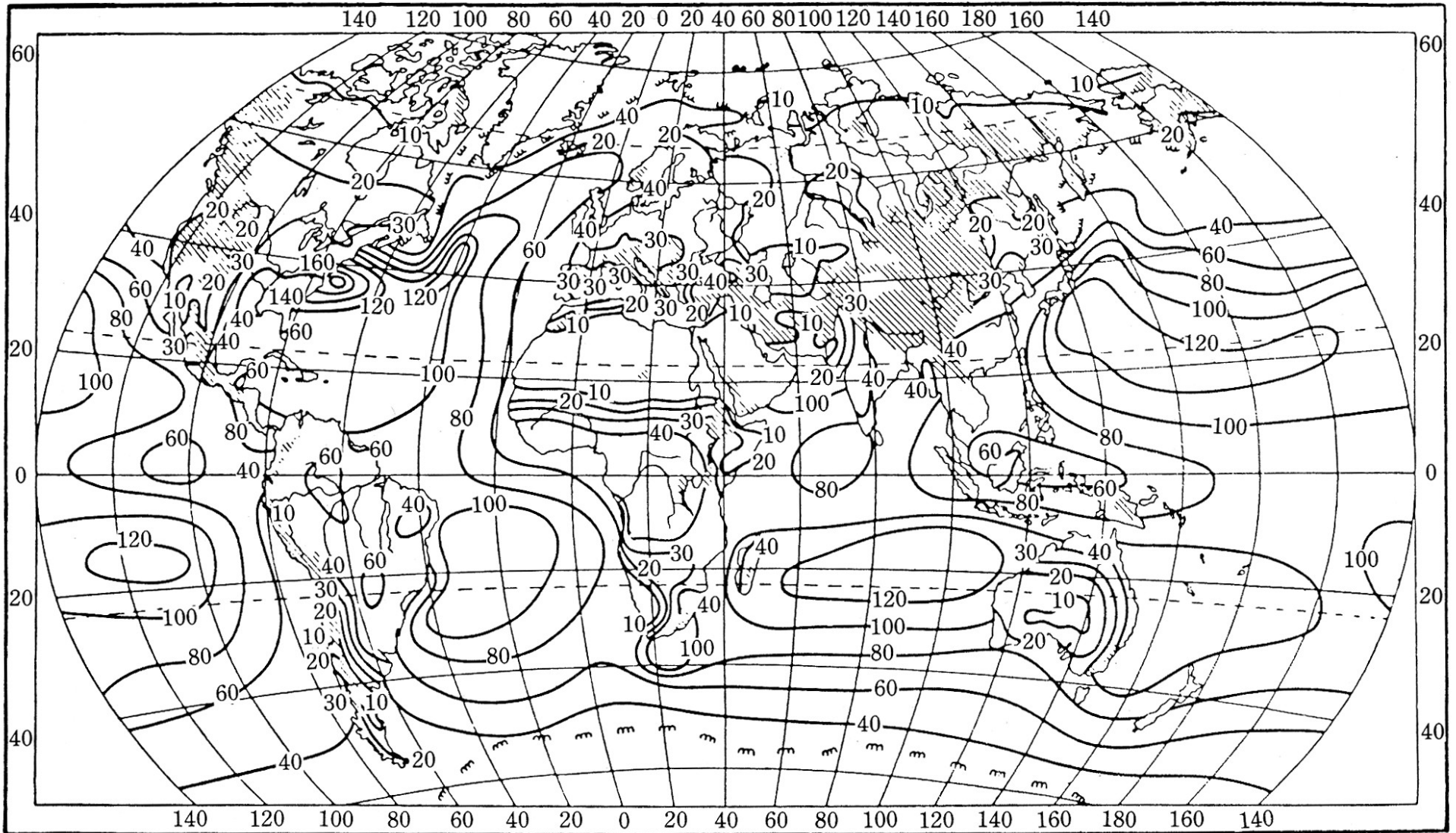
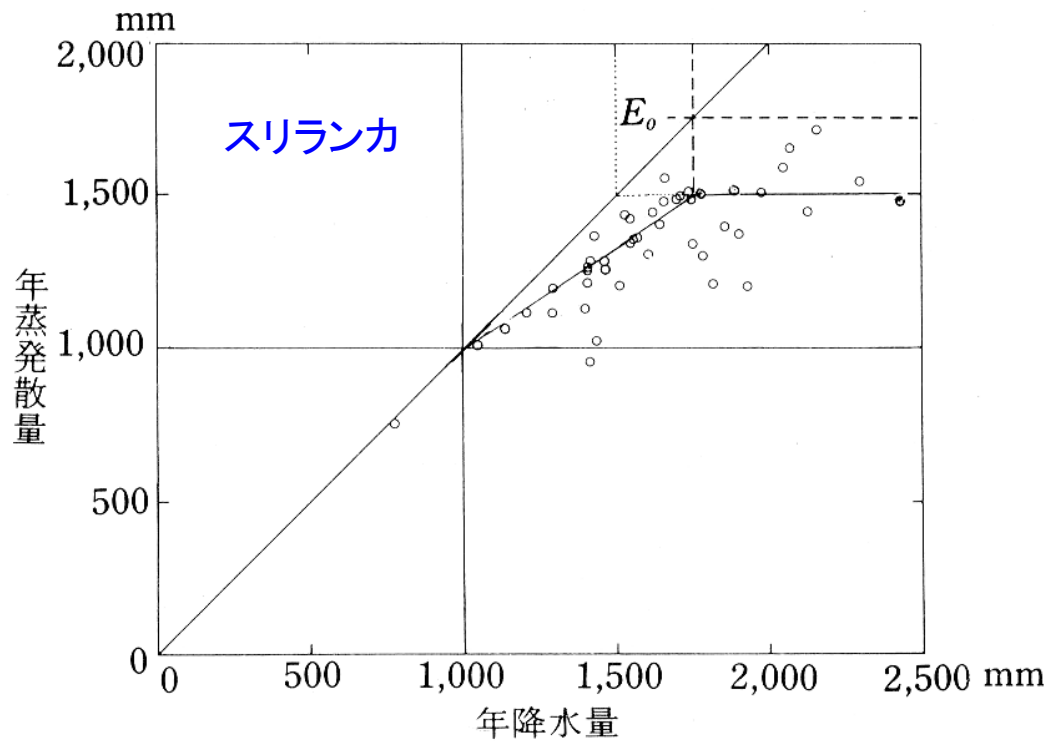


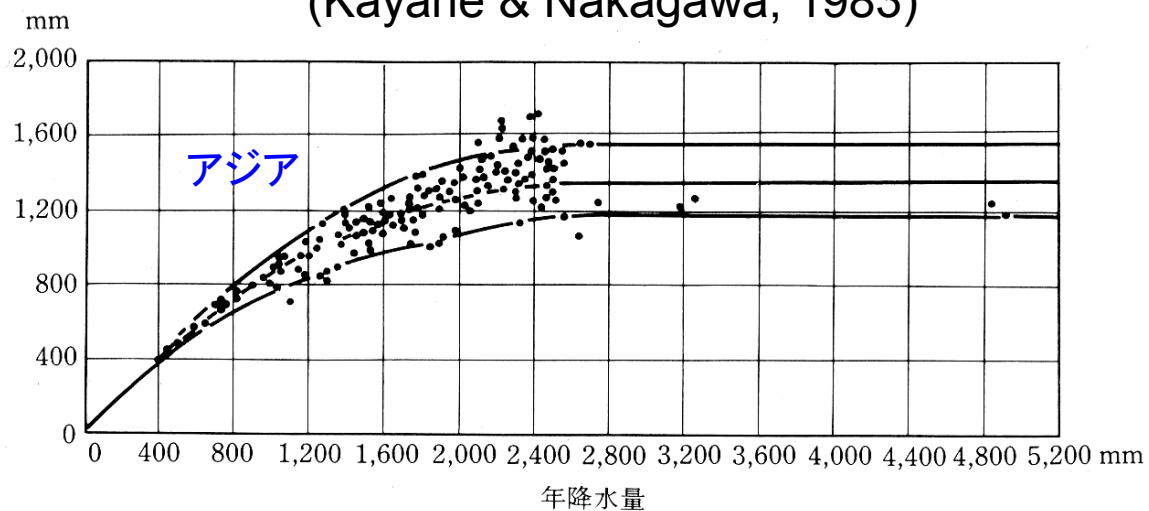
図 62 蒸発による年潜熱フラックス(kcal·cm<sup>-2</sup>·yr<sup>-1</sup>)の世界分布図(Budyko, 1963)



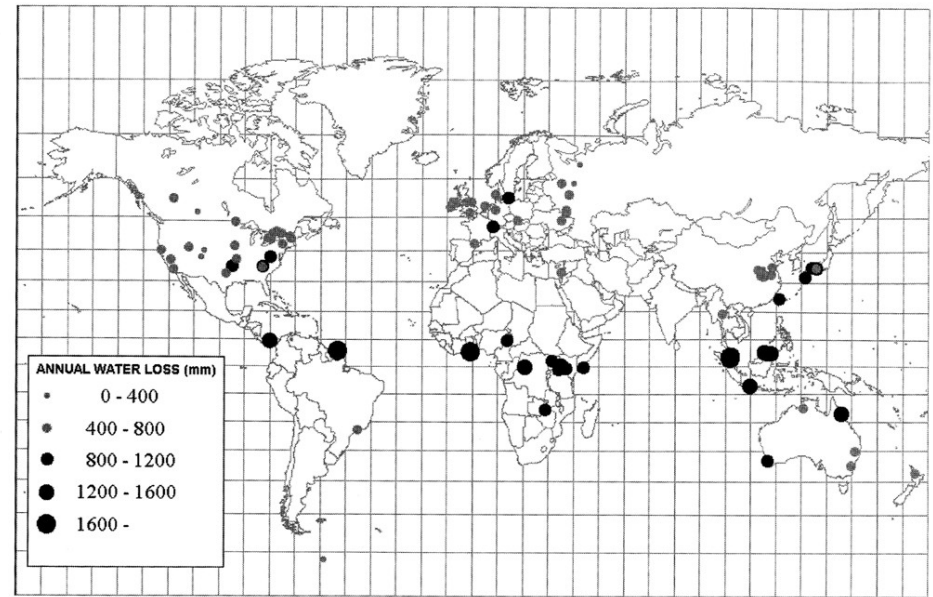
# 流域水収支法による年実蒸発散量



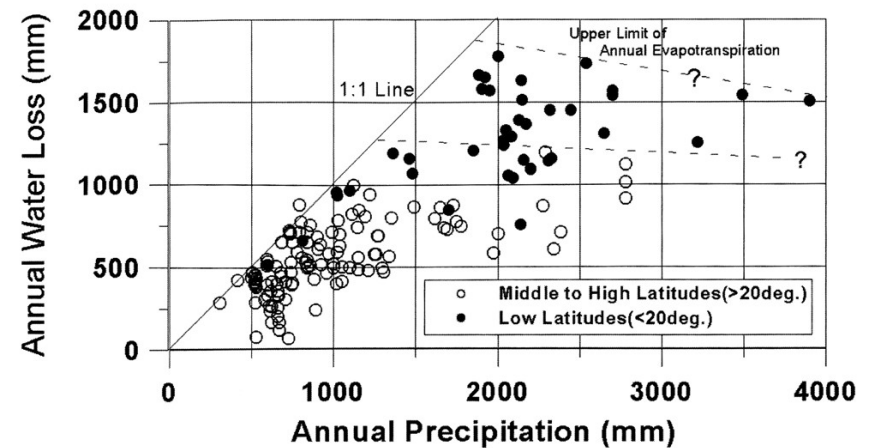
(Kayane & Nakagawa, 1983)



(Solomon, 1969)



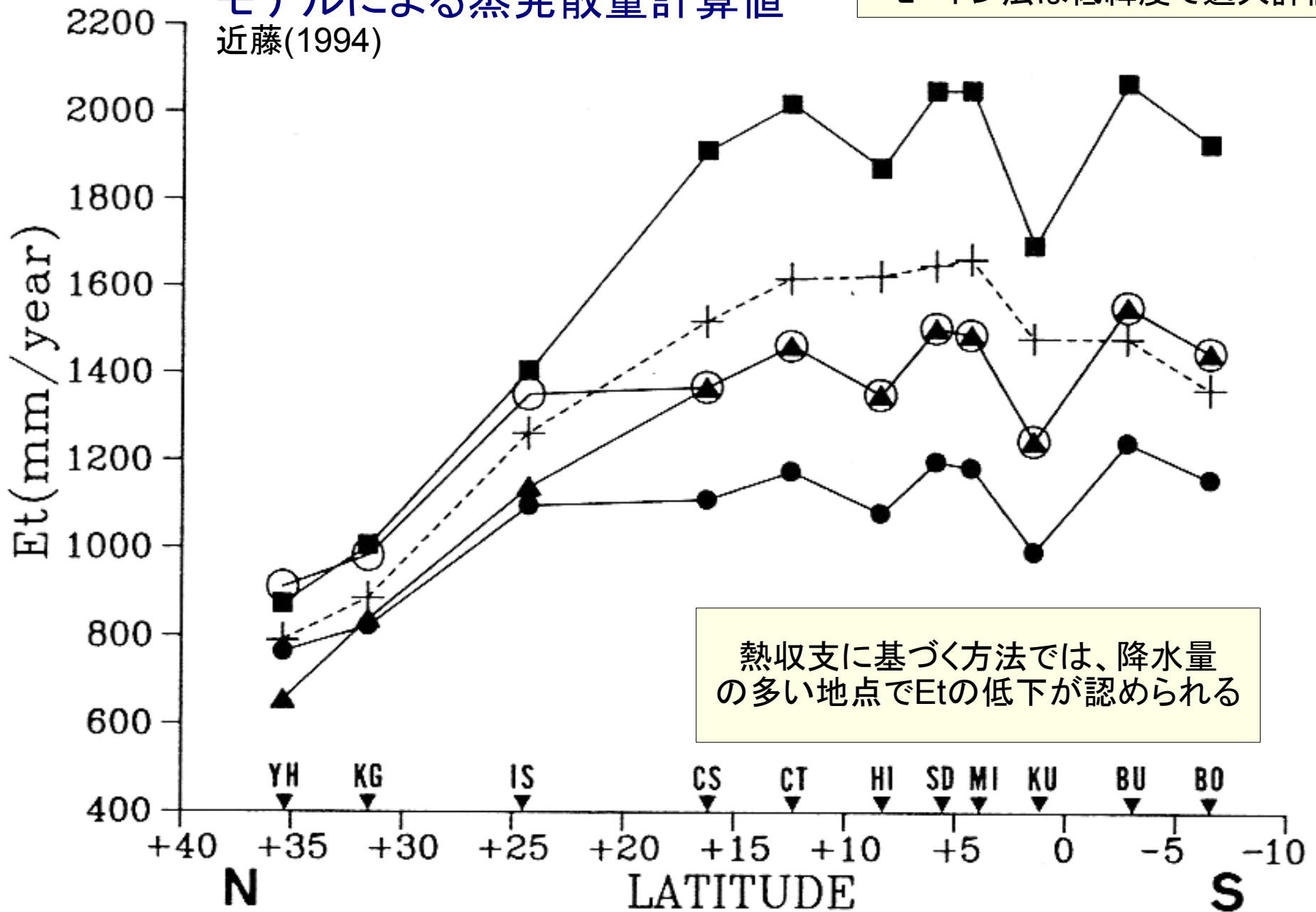
(Kondoh *et al.*, 1999)



# モデルによる蒸発散量計算値

近藤(1994)

モートン法は低緯度で過大評価



熱収支に基づく方法では、降水量の多い地点でEtの低下が認められる

- : Penman (1948)  $\rho$  (albedo) = 15%, ○ : Penman (1948)  $\rho$  = 5%,
- : Morton (1983), ▲ : Fitzpatrick and Stern (1965)  $\rho$  = 15%.

# 第9回：特定地域の水文学Ⅰ

## モンスーンアジアの水文地域

### 【学んだこと】

- **水文地域は地域研究を統合する  
フレームワーク**
- **水収支の地域性の理解が、地域の  
水問題に対処する際の最初のステップ**

