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WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 144

RICE AND WEATHER

by

G. W. ROBERTSON

CAgM Rapporteur on Meteorological Factors
Affecting Rice Production

WMO — No. 423

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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THE WMO

The World Meteorological Organization (WMO) is a specialized agency of the United Nations of which 144 States and Territories are Members.

It was created:

- To facilitate international co-operation in the establishment of networks of stations for making meteorological and geophysical observations and centres to provide meteorological services and observations;
- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological observations and ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture, and other human activities;
- To encourage research and training in meteorology.

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The *World Meteorological Congress*, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The *Executive Committee* is composed of 24 directors of national Meteorological Services and meets at least once a year to conduct the activities of the Organization and to implement the decisions taken by its Members in Congress, to study and make recommendations on matters affecting international meteorology and the operation of meteorological services.

The six *Regional Associations* (Africa, Asia, South America, North and Central America, South-West Pacific and Europe), which are composed of Member Governments, co-ordinate meteorological activity within their respective Regions and examine from the regional point of view all questions referred to them.

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UDC 551.586: 633.18

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1975

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ISBN 92 - 63 - 10423 - 9

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FOREWORD

The urgent need to increase the world's food production is now recognized on all sides. In many countries, in tropical and subtropical areas, this need implies increasing rice production and much attention has in fact been given to this subject, including the introduction of new high-yielding varieties of rice which produce yields near the limit of the climatic potential for a given area. These crops, however, are more susceptible than before to seasonal variations in the weather. Agronomists, crop ecologists, production co-ordinators and marketing analysts have therefore become increasingly aware of the role of weather variability in plant breeding and selection, and in annual variations in crop production.

In these circumstances, the WMO Commission for Agricultural Meteorology decided to appoint in 1972 a Rapporteur on Meteorological Factors Affecting Rice Production, as a follow-up of the earlier work on the subject. Mr. G. W. Robertson (Canada) agreed to serve in this capacity. The task of the rapporteur was to review the present knowledge of the climatological factors defining areas suitable for the production of rain-fed, dry-land rice, and to review the present knowledge of the threshold values of the climatological factors which set limits on the profitable production of specified varieties of rain-fed, dry-land rice. Mr. Robertson accordingly prepared a report on this subject, which now constitutes the present publication.

It is with great pleasure that I take this opportunity of extending to Mr. Robertson the appreciation of the World Meteorological Organization for the time and effort he has devoted to the preparation of this Technical Note, which I am sure will be of great interest to agrometeorologists, research workers in agriculture, and all those concerned with rice production.

D. a Davies.

D. A. Davies
Secretary-General

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SUMMARY

Rice is the basic food for more than half the population of the world. The crop grows mainly in the plains of tropical and subtropical regions under continuously flooded conditions. Some varieties are adapted to dry-land farming conditions in upland areas while others will develop and mature in colder climates as far north as 43° of latitude. Thousands of strains or varieties have evolved over the centuries and each of these has its own genetic characteristics adapting it to the specific environmental conditions of local areas. In general, rice requires a growing period of 120 to 150 days with a short photoperiod, less than 14 hours, temperatures above 15°C, sufficient water for the rate of evapotranspiration to be near the potential, and abundant sunshine. Although the humid tropical and subtropical areas appear to be well suited to rice production, maximization of production requires a great deal of technical skill in selection and manipulation of varieties which are attuned to the specific environmental conditions of a given area. Many areas have bioclimatic limitations which may restrict the potential yield of rice. Agrometeorology can play a very important role in quantifying these conditions and interpreting them in terms of expected production.

RÉSUMÉ

Le riz est l'aliment de base de plus de la moitié de la population du globe. Cette plante est cultivée principalement dans les plaines des régions tropicales et subtropicales, sur des terrains constamment inondés. Certaines variétés sont adaptées à la culture sèche, sur des terrains plus élevés, tandis que d'autres peuvent se développer et arriver à maturation dans des climats plus froids, jusqu'à 43° de latitude nord. Des milliers de variétés sont apparues au cours des siècles, chacune ayant des caractéristiques génétiques qui font qu'elle est adaptée aux conditions particulières du milieu propre à chaque zone de culture. En général, le riz exige une période de croissance de 120 à 150 jours avec photopériode brève, moins de 14 heures, une température supérieure à 15°C, suffisamment d'eau pour que l'évapotranspiration soit proche de la valeur maximale possible, et une forte insolation. Bien que les zones tropicales et subtropicales humides soient bien adaptées, a priori, à la production du riz, pour obtenir la production maximale, une forte technicité est indispensable, afin de pouvoir choisir et manipuler à bon escient les variétés qui sont les mieux adaptées aux conditions particulières du milieu d'une zone donnée. Dans un grand nombre de régions, certains facteurs bioclimatiques peuvent limiter le rendement potentiel du riz. La météorologie agricole peut jouer un rôle très important en permettant de quantifier ces conditions et de les interpréter de manière à en déduire la production prévisible.

РЕЗЮМЕ

Рис является основным продовольствием для более чем половины населения земного шара. Культура произрастает в основном на равнинах в тропических и субтропических районах при продолжительных паводках. Некоторые разновидности адаптируются к условиям возделывания в сухой земле в гористых районах, в то время как другие произрастают и развиваются в более холодном климате значительно севернее 43° с. ш. Тысячи сортов и разновидностей появились в течение веков и каждый из них имеет собственные генетические характеристики, которые приспосабливают их к специфическим условиям окружающей среды в местных районах. Как правило, рису необходим период произрастания от 120 до 150 дней, а также короткий фотопериод менее 14 дней, температура выше 15°С, достаточное количество воды, чтобы величина эвапотранспирации была близкой к потенциальной, а также обилие солнечного света. Хотя влажные тропические и субтропические районы являются весьма подходящими для производства риса, увеличение производства риса требует значительного технического опыта в селекции и манипуляции разновидностями, которые настраиваются на специфические условия окружающей среды данного района. Многие районы имеют биоклиматические пределы, которые могут ограничить потенциал урожая риса. Агрометеорология может сыграть весьма значительную роль в определении этих условий и их интерпретации с точки зрения ожидаемого производства риса.

RESUMEN

El arroz constituye el alimento básico de más de la mitad de la población mundial. Principalmente se cultiva en las llanuras de las regiones tropicales y subtropicales en condiciones de inundación permanente. Algunas variedades se han adaptado a condiciones de cultivo en tierras secas situadas en regiones elevadas, mientras que otras se desarrollan y maduran en climas más fríos hasta una latitud norte de 43°. A través de los siglos se han ido desarrollando miles de clases y variedades de arroz, cada una con sus propias características genéticas que la hacen adaptable a las condiciones ambientales específicas de las diferentes zonas locales. En general, el arroz requiere un período de crecimiento comprendido entre 120 y 150 días, con un breve fotoperíodo, inferior a 14 horas, temperaturas superiores a 15°C, agua suficiente para que el índice de evapotranspiración se aproxime al potencial, y abundante insolación. Aunque las regiones tropicales y subtropicales húmedas parecen reunir excelentes condiciones para la producción de arroz, si se quiere maximalizar esta producción es necesario un gran bagaje de conocimientos técnicos para la selección y manipulación de las variedades que se acomodan a las condiciones ambientales específicas de una determinada región. Muchas regiones tienen limitaciones bioclimáticas que pueden restringir el rendimiento potencial del arroz. La agrometeorología puede desempeñar una función muy importante en la cuantificación de estas condiciones, así como en la interpretación de las mismas en términos de producción prevista.

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CHAPTER 1

RICE CULTIVATION

1.1 Distribution

Rice is the basic food for more than half the population of the world (Anonymous, 1966). This is no accident when it is considered that rice is adapted to a greater range of climatic conditions than any other single cereal species.

Nearly ten per cent (131.2 million ha) of the world's agricultural lands are used for paddy (unhusked rice) production (*Table I*). About 90 per cent of this is in the Far East and on the China mainland, where the population is nearly 1 900 million. Most of the 295.4 million metric tons of paddy produced in the world is grown for local consumption. Only 11.1 million metric tons, or 3.8 per cent, of the world's production enters the export trade (Anonymous, 1972*b*).

TABLE I

World population, arable land and paddy[1] production in 1972

(*F.A.O. Production Yearbook—1972*)

Region	*Population* (in 10^6)	*Agricultural*[2] *area* (10^6 ha)	*Paddy area* (10^6 ha)	*Paddy yield* (100 kg/ha)	*Paddy production* (*metric tons* × 10^6)
Far East	1 056	269	78.6	17.8	140.0
China (mainland)	801	111	33.8	30.9	104.3
South America	201	84	6.1	16.7	10.2
Africa	363	214	4.2	17.8	7.4
Near East	182	85	1.2	37.5	4.5
North and Central America	330	271	1.4	38.5	5.3
Europe	467	145	0.4	40.3	1.6
U.S.S.R.	247	233	0.4	38.9	1.6
Oceania	201	47	—	55.1	0.3
World total	3 761	1 457	131.2	22.5	295.4

[1] Unhusked rice

[2] Excluding forest areas

Rice is indigenous to the humid areas of tropical and subtropical regions. Since most varieties grow best under flooded conditions, rice is found in coastal lowlands, flood plains and river deltas. Ideal regions are in the deltas of rivers having their headwaters in high, forested hills or mountains which provide a source of spring water for continuous streamflow, even during the dry season.

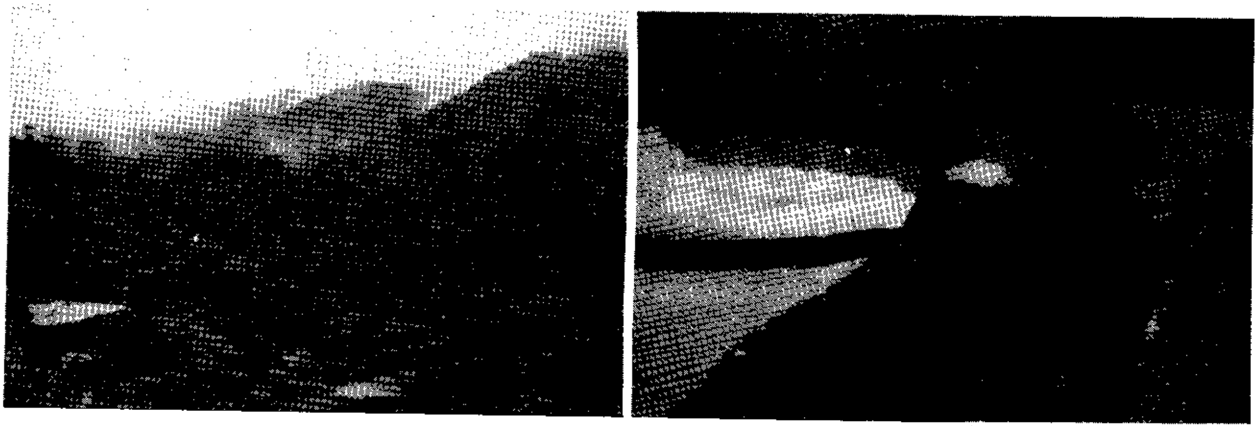
Historically, rice was probably first cultivated in the lowlands of the humid tropics in South-East Asia. As populations grew and more land was needed, rice-growing areas gradually expanded from the delta areas to the alluvial soils along the river valleys. To retain water continuously on rice fields, low dikes or levees had to be constructed (see *Plate I*, p. 2). As the demand for more rice land increased, these diked paddies became smaller and were extended up hillsides of increasingly greater slope. The results were the extensively terraced hillsides in many parts of South-East Asia, the most famous being in the vicinity of Banaue in the Philippines (see *Plate II*, p. 2). Where terraces could not be built to hold water, rice varieties were found which could be grown during the rainy season as a dry or upland crop without the necessity of flooding.

PLATE I—RICE PADDY PREPARATION

(*Photograph by the rapporteur*)

Rice cultivation is one of the oldest agricultural activities in many areas of the far east, predating by many centuries the arrival of Europeans in the area. Cultivation procedures have changed but little down through the ages. Shortly after the beginning of the rainy season, when there is sufficient water to flood the paddy, preparation of the land begins. The water buffalo, or caraboa *as it is called in the Philippines, is the main source of power and is still competitive with modern motorized machinery. Simple equipment is used: a small walking-plough to break up the heavy clay followed by several passes of a combed-tooth harrow. The soil is worked until it is thoroughly puddled. Rice seedlings are then transplanted by hand at the rate of four plants per hill and about 165 000 hills per hectare. The farm size varies greatly but averages between three and four hectares.*

PLATE II—RICE TERRACES OF BANAUE



(*Photographs by the rapporteur*)

The rice terraces of Banaue were built by the Ifugao tribes in the mountains of north central Luzon, the largest island of the Philippine group. These agricultural wonders were built over 3 000 years ago without the aid of modern engineers, hydrometeorologists or power equipment. They rise above deep mountain valleys up slopes often as steep as 45° to altitudes near 1 500 m above m.s.l. These ancient and wonderful hydrological structures are probably one of the most marvellous of water-control systems in the world today. They provide flood and erosion control and serve as reservoirs for irrigation water. Even today there are tribal taboos which prohibit the cutting of sacred forest trees on the tops of hills and mountains above the terraces. It appears that these forests above 1 500 m intercept a vast quantity of cloud droplets which keeps springs and streams trickling to replenish water in the terraces below during the dry season. Although the main crop is rice, many varieties of vegetables are grown during the dry season on those terraces which do not receive sufficient water for rice production. These terraces have frequently been referred to as the eighth Wonder of the World.

1.2 Varieties

There are two main rice varieties and well over 2 000 strains of these have developed by natural plant selection over centuries of cultivation. These strains have subtle differences in characteristics which make each desirable in the area where it is grown: matching the seasonal weather trend; being resistant to local diseases; meeting the local requirements for planting and harvesting traditions; and having the desired taste and cooking quality preferred by the local consumers.

Indica varieties* are grown mainly in tropical countries. Characteristically they are tall (over 150 cm), leafy, profuse tillering and photoperiodically sensitive, making the period of maturity variable, depending on the planting date. These varieties are generally low-yielding but reliable year after year. Their main disadvantage is their susceptibility to lodging, often before flowering. This leads to low yields, harvesting difficulties, and low-quality grain.

The *japonica* varieties are common in subtropical and low, temperate latitudes. They are short and usually early and high yielding. Some varieties have thick, tough leaves which can withstand strong winds. Others have tolerance to cold, a desirable characteristic in high latitudes and in high elevations in the tropics. However, their ability to tiller is limited, they are susceptible to many diseases, they have weak stems and their eating quality is not acceptable to many people in tropical areas. They also lack seed-dormancy, a desirable characteristic when seed is harvested during wet weather.

New miracle varieties of rice developed at the International Rice Research Institute (IRRI) in the Philippines are results of selections from crosses of the most desirable strains of *indica* and *japonica* varieties and of the many strains of vigorous, short-strawed types from the U.S.A. The main characteristics of these new varieties are short straw, upright leaves, non-lodging, good response to nitrogenous fertilizers, high tillering rate, insensitivity to photoperiod and, therefore, early maturing. All these characteristics lead to high yields (Anonymous, 1972*a*).

1.3 Soils

Rice will grow on a great variety of soil types. Heavier clay soils with 50 to 60 per cent finer fractions of silt and clay are preferred. In order to retain water in the paddy it is essential that an impervious layer of fine-textured soil (clay) exist within two to five feet of the surface. Although rice will tolerate a wide range of soil acidity from pH 4.5 to 8.7, best yields are obtained on neutral to slightly acidic soils.

1.4 Cultural techniques

In the humid tropics, flooded rice can be grown either under rain-fed or irrigated conditions. The general cultural techniques are similar for both. The main difference is that, for rain-fed rice, planting operations are timed to coincide with the beginning of the wet or rainy season if one exists. If the wet season is long enough, two crops can be taken off one piece of land. On the other hand, where the wet season extends throughout the year or where irrigation can be practised, plantings can be made at any time of the year and as many as three rice crops can be grown each year on one piece of land.

In subtropical and temperate zones the factor controlling the beginning and ending of the rice-growing period is temperature: *indica* rice varieties require a minimum temperature above 20°C while the *japonica* varieties will tolerate temperatures as low as 15°C.

Rice seedlings are usually started in a nursery and later transplanted in the paddy. A nursery of 300 to 500 m^2 and planted with 40 kg of seeds will produce sufficient plants for a one-hectare field. Before planting, the seeds are soaked and pregerminated in warmth for 36 to 48 hours. Under flooded conditions in the nursery for 20 to 30 days the seedlings reach the fifth-leaf stage with a height of 15 to 20 cm, when they are ready for transplanting.

In temperate regions (Japan) the nursery may be heated by suitable means to hasten the growth of seedlings (Inoue *et al.*, 1965).

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* Much of the following information has been summarized from the *Rice Production Manual* (Anonymous, 1970*a*).

Pregerminated seeds with radicle (hypocotyl) measuring 1 to 2 mm long can be broadcast on the surface in unflooded fields. However, such seedlings are subjected to damage by birds, rats and snails and may be washed away by heavy rains before taking firm root. Where fields are large enough and suitable machinery is available, dry seeds can be drilled into non-flooded, prepared seed-beds at a depth of 25 to 50 mm.

In tropical Asia most rice is grown in small flooded paddies where the seedlings are transplanted by hand. Paddies are prepared as soon after the beginning of the rainy season as possible. After the land becomes flooded, it is plowed and harrowed several times until the soil is thoroughly puddled. This puddling not only helps to kill weeds and incorporate organic material into the soil but also makes it easy to transplant seedlings. The preparation of the soil and nursery plants requires careful timing in relation to the beginning of the wet season. Often the onset of the wet season may be delayed by several weeks, making it difficult to time the availability of nursery stock to coincide with land preparation.

Seedlings are transplanted by hand, either randomly or in rows. Plant spacing varies with the variety but ranges from 20 × 20 cm to 35 × 35 cm.

CHAPTER 2

GROWTH AND DEVELOPMENT

2.1 Pattern

Rice follows a definite pattern of growth and development regardless of the method of planting and watering and of the variety used. The period from seed germination to seed maturity, the life cycle of the plant, can be divided into three distinct physiological or phenological phases of development and each of these into two or more periods (Anonymous, 1970*a*; Ishizuka *et al.*, 1973).

2.2 Vegetative phase

This phase includes the interval from seed germination to panicle initiation and includes three periods. (1) The seedling period is from the time of germination until the fifth-leaf stage. During this period young plants develop seminal and lateral roots while absorbing nutrients from the endosperm of the seed. (2) The transplanting period covers the interval from the fifth-leaf stage to full recovery following transplanting. This usually takes about three weeks. (3) The period of tillering follows closely after the fifth-leaf stage and recovery from transplanting. Tillers arise from buds in the axil of the leaf at each node. When space and fertility are optimum, as many as 100 tillers may be produced by some varieties. Usually the tillers are limited under normal field conditions from two or three per plant for machine-seeded rice in rows, to 25 or 30 for transplanted plants with a spacing of 20 × 20 cm. Often more tillers are formed than can be supported by the plant and many late ones die back. The tillering period lasts about 30 to 50 days, the duration being sensitive to temperature and photoperiod. Near the end of the tillering period, or sometimes before the end, the initiation of the panicle primordia in the tillers takes place. This marks the beginning of the second or reproductive phase.

2.3 Reproductive phase

This phase consists of four distinct periods. (1) The panicle initiation period may be very short: following, coinciding with or starting shortly before the stage of maximum tillering in varieties insensitive to photoperiod. This period may be of several weeks' duration in photoperiod and temperature sensitive varieties. (2) The period of internode elongation or booting begins immediately after initiation of the primordia. During this period the expanding primordia is pushed upward inside the flag-leaf sheath by the elongation of the upper internodes of the stem. (3) The emergence of the panicle from the flag-leaf sheath marks the beginning of the third or heading period followed almost immediately by (4) the flowering period. The time interval from panicle primordia initiation to flowering averages about 23 days (*Table II*).

2.4 Ripening phase

The ripening phase consists of three periods. (1) The milk period occurs when the starchy portion of the grain (the caryopsis) develops from a watery to a milky consistency. (2) During the dough period the caryopsis loses its milky consistency and becomes gummy (soft dough), then hardens to the hard-dough stage. (3) During the final period, maturation, the kernels become fully developed, hard, clear grains of rice which lose their greenish tint when the moisture content drops below 26 per cent. During the maturation period the leaves become senescent and turn yellowish in ascending order and, along with the culm, become non-functional. The culm and upper leaves of some varieties may remain green even after the kernels have ripened, particularly under high fertility and

TABLE II

Phenological data

Station		*Average date of sowing*	*Days from sowing to:*[1]						
No.	*Name*		E	T	MT	PPI	H	DS	M
1	Kpong	March 15	5	—	60 e.v.[2]	75 e.v.	90 e.v.	105 e.v.	122
2	Kpong	Sept. 15	5	—	60 e.v.	75 e.v.	90 e.v.	104 e.v.	122
3	Nyankpala	June 15	5	—	61	82	107	122	137
4	Pattambi	June 3	3	29	60	65	96	119	133
5	Pattambi	Sept. 30	2	34	59	62	93	112	122
6	Los Baños	June 16	3	20	60	88	103	119	133
7	Los Baños	Dec. 16	3	20	60	75	90	106	120
8	Tai Lung Farm	March 15	7	31	61 e.v.	85	92	115	122
9	Tai Lung Farm	July 1	2	32	56 e.v.	79	84	106	118
10	Tshaneni	Oct. 1	14	—	60	85	115 e.v.	130 e.v.	150
11	Crowley	April 1	6	—	34	62 e.v.	95	108	122
12	Pelotas	Nov. 9	6	—	60 e.v.	72	102	118 e.v.	131 e.v.
13	Concepción del Uruguay	Oct. 30	16	—	31	92	103	123 e.v.	151
14	Chikygo-Shi	May 25	3	29	69	82	104	126	158
15	Stoneville	May 1	7	—	67	67	113	132	147
16	Yanco	Oct. 5	20	—	61	92 e.v.	125	161	184
17	Stuttgart	May 1	9	—	65	74	108	128	138
18	La Plata	Oct. 5	25	—	102	102	123	151	166
19	Takado	April 15	7	46	91	107	122	143	168
20	Ridgetown	May 26	17	—	55 e.v.	50 e.v.	78	94 e.v.	112 e.v.
21	Hokkaido Expt. sta.	April 25	6	30	86	73	104	129	157
22	Asahikawa	April 20	7 e.v.	35	86	81	107	131 e.v.	158
Averages			8	29	64	79	102	122	139

1. E—emergence; T—transplanting; MT—maximum tillering; PPI—panicle primordia initiation; H—heading; DS—dough stage; M—mature;
2. e.v.—estimated values for days.

disease-free conditions. The ripening phase, from anthesis to full maturity, averages about 35 days but varies depending on temperature. The total time from germination to full maturity ranges from 90 to 200 days depending on the variety and its response to photoperiod and temperature, particularly during the vegetative phase.

2.5 **Yield**

Rice yield is quite variable from farm to farm and from country to country. Many factors such as native fertility of the soil, farm management practices, variety, prevalence of diseases and insects, and the weather are responsible for this variation. The lowest yields, 1 400 to 2 000 kg/ha, are reported from developing countries in South America, Africa, and the Far East where native fertility of the soil is low and management practices are marginal. In the developed countries of Europe, North America and Australia, where high-yielding varieties are used and optimum farm management is practised, the farm yields range from 4 800 to 5 300 kg/ha. At IRRI in the Philippines high-yielding varieties under optimum management have been made to yield at the rate of 25 650 kg/ha per year. This was achieved by planting four successive crops on one plot throughout the year. Individual crop yields were 8 780 kg/ha, 5 350 kg/ha, 6 350 kg/ha and 5 170 kg/ha. Because of the expensive input and painstaking management this type of production and yield is out of reach of the practical farmer but it does illustrate the potentially high productivity which humid tropical climates will support (Anonymous, 1972*c*).

Another important consideration in connexion with high-yielding rice varieties is the effect of weather variability from season to season. As yields approach the climatic potential of a region they become more susceptible to variations in weather. This is well illustrated by data from Japan where high-yielding varieties have been pushed to the limits of their temperature tolerance. In the Kitami district of Hokkaido, where conditions are only marginal for rice production, the yield of brown rice in an average season is 3.3 metric tons per ha (t/ha). In a very good season yields are in excess of 6.0 t/ha while in a season of very cool weather they will drop to 1.5 t/ha (Ishizuka *et al.*, 1973).

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CHAPTER 3

ENVIRONMENTAL REQUIREMENTS

3.1 Water

The main environmental characteristic which sets rice apart from other cereal crops is its water requirement. Rice is the only cultivated crop which thrives under flooded conditions. Although there are varieties which will grow under dry-land or upland conditions, these occupy only about 20 per cent of the total land area devoted to rice in South-East Asia. Another 20 per cent is irrigated, but as much of the irrigation is done with diversion-dam systems, many crops are often at the mercy of floods and droughts. The remaining 60 per cent is grown under rain-fed conditions and is subject to the full impact of seasonal droughts and floods.

Although rice will tolerate a wide range of water conditions in the field, the optimum appears to be sufficient just to cover the soil (Matsushima, 1962). Greater amounts up to a depth of about 15 cm have little effect on plant growth and yield. The optimum depth from a practical point of view appears to be about 5 cm. One danger of shallower water is the problem of maintaining a flooded condition, particularly during periods of high evaporation with no rain and an inadequate supply of irrigation water. If the soil is allowed to dry, yields are depressed possibly because of increasing water stress in the plant. The rooting depth of rice is very shallow, about 15 cm, and water stress in the plant can develop quickly. Weed growth is difficult to control in an unflooded paddy. In many upland areas, where dry-land farming is practised continuously, grasses soon take over the land because the primitive cultivation equipment in use is inadequate to cope with grasses.

Tiller formation appears to be stimulated by the large diurnal variation of soil and water temperature which is favoured by shallow water: warmer water in the day-time and cooler at night. This, in turn, increases the number of tillers and ultimately the yield. Shallow water also favours decomposition of organic matter which stimulates the development of the root system. This increases the nutrient intake by the plant and decreases the chances of water stress within the plant (Chapman, 1969; Inoue *et al.*, 1965; Rose and Chapman, 1968).

The most critical stage when water is required in the life cycle of the rice plant occurs during the latter part of the vegetative period from panicle primordial initiation to about five days after heading (Sreenivasan and Banerjee, 1973).

Deep flooding of rice has several deleterious effects on the rice crop. Oxygen available to the root system is reduced and soil toxicity may result. Water temperature may be low, particularly at higher latitudes and elevations, resulting in slow decomposition of organic material and low tillering rates. Plants in deep water tend to be taller and lodge more easily. Where water is very deep, photosynthesis may be affected, particularly if the plant is completely submerged for a week or longer (Palada and Vergara, 1972). At the time of pollination, complete submergence will result in failure of seed-set. Many of these effects of deep water on rice production depend on the variety of rice being used. Often local varieties will withstand severe flooding. A noted example is the so-called floating varieties of Thailand (Yantasast *et al.*, 1970). These varieties have stems up to six metres in length and will produce grain so long as the upper leaves and panicles float above the water. Such varieties will survive the severe flooding which occurs in the delta areas of many rivers during abnormally wet monsoon seasons.

Deep flooding (over 15 cm) can have some advantages. The greater mass of water controls the water and soil temperature during extremely hot or cold periods. Weed control (particularly grass) is more complete. Water management is easier and requires less attention. The greater depth of water may provide a reserve for short dry spells (Chapman and Kininmonth, 1972).

Evapotranspiration by a rice crop approaches the potential rate, since the paddies are flooded and adequate water is available for the process. In smaller paddies actual evapotranspiration may exceed the potential rate due to the horizontal advection of sensible heat into the crop (Evans, 1971). Evapotranspiration depends on the intensity of the global solar radiation and the rate of advection of sensible heat. In the humid tropics, where the winds are frequently light and the atmospheric water-vapour pressure deficit is small, the daily evapotranspiration rate is dependent largely on the available global solar radiation. Daily evapotranspiration averages about 4.0 mm during the rainy season, when skies are frequently cloudy, and about 5.5 mm in the dry season, when skies are clearer and global solar radiation is greater (Asuncion, 1971).

Other serious water losses from the rice paddy are caused by seepage, percolation and surface drainage. Seepage and percolation are higher during the dry season when the groundwater table is low and may range from 0 to 6.5 mm per day depending on soil type and proximity to drainage channels. During the wet season seepage and percolation losses are usually much smaller, ranging from 0 to 2.5 mm. Surface drainage, on the other hand, may be quite high during the wet season, depending on the intensity of rainfall (Chapman and Kininmonth, 1972).

The total water requirements for rice crop are therefore quite high throughout this whole period and vary considerably, ranging from 1 000 to 3 000 mm for wet-season crops and from 700 to 2 500 mm for dry-season crops requiring 120 days from transplanting to maturity. The efficiency of water use in rice paddies varies widely from 35 per cent during the wet season to 70 per cent in well-managed systems during the dry season. The total amount of irrigation water required depends upon seepage, percolation, evapotranspiration, runoff, and amount and distribution of rainfall as well as the length of growing season.

Rice will not produce a profitable crop on stored soil moisture (capillary water) or infrequent rains as will wheat and other cereals.

3.2 Photoperiod

Broadly speaking, rice may be regarded as a short-day plant (Vergara *et al.*, 1969). This is not surprising when it is considered that the species originated at low latitudes where the day-length is naturally short. What is surprising is that the rice plant has developed a great sensitivity to the small changes in daylight which occur in low latitudes as the sun moves north and south across the Equator throughout the year (*Figure 1*). This sensitivity appears to have developed as a natural control to bring the date of flowering into coincidence with the end of the wet season in a monsoon climate. This control is essential since planting by hand labour in developing countries is slow and extends over a long period of time. However, due to the photoperiodic control of the initiation and development of the panicle, all fields will ripen at about the same date at the end of the wet season, regardless of

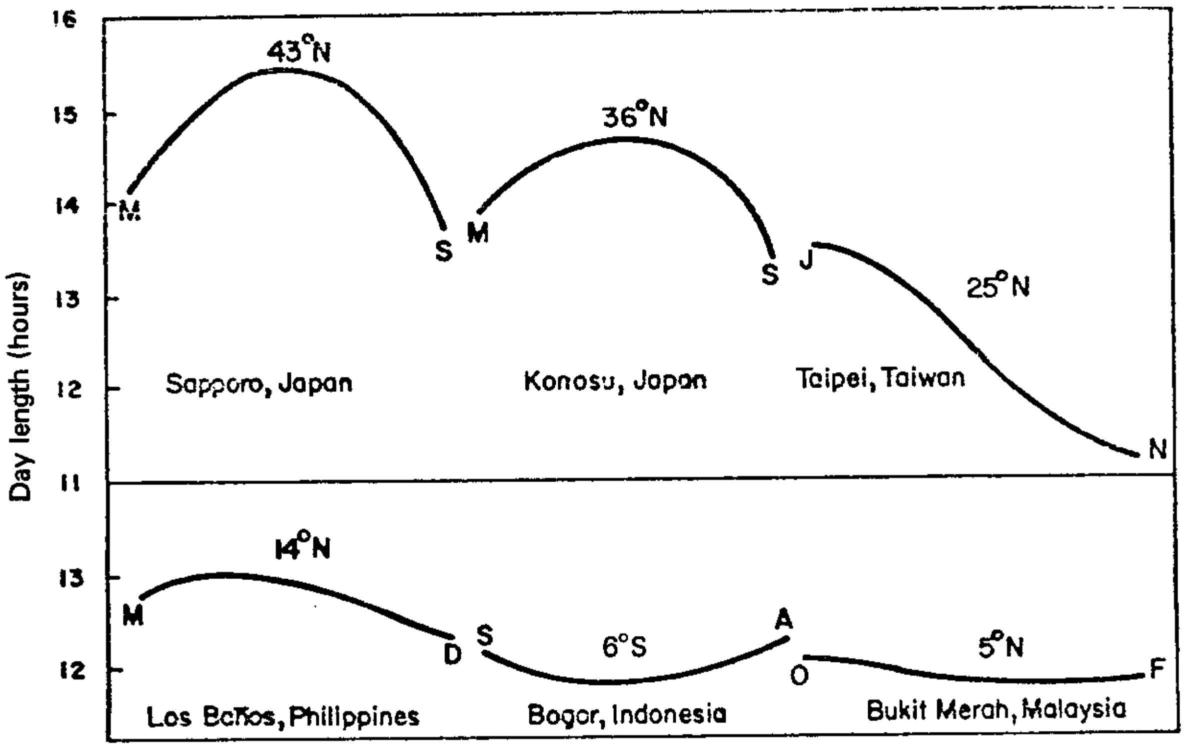

Figure 1—Day-length patterns during the main crop season at six locations in Asia (Anonymous, 1970*a*).

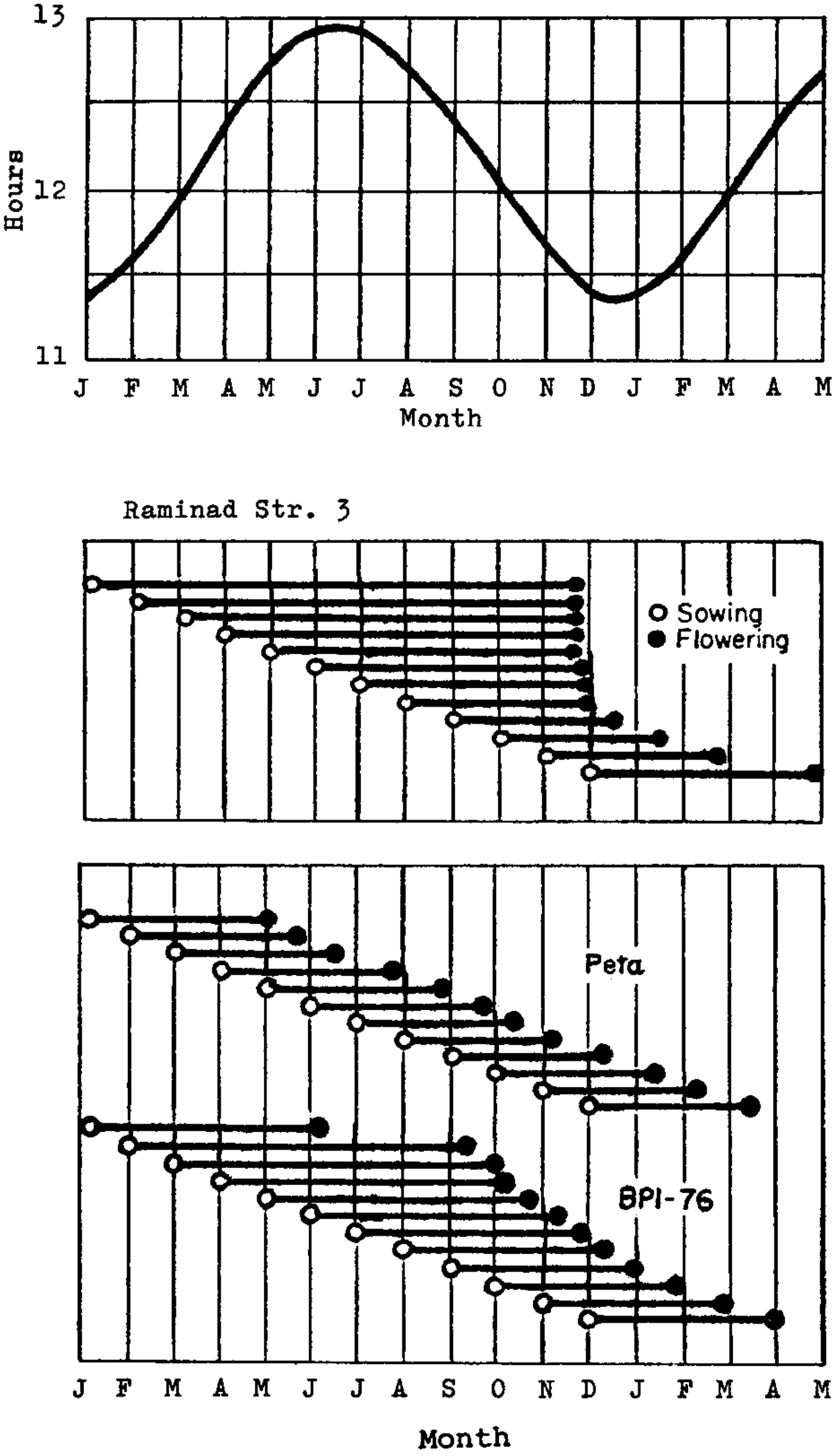

Figure 2—Date of planting and flowering of Raminad Str. 3, Peta and BPI-76 and fluctuations in day-length at Los Baños, Laguna (Anonymous, 1970*a*).

the date of planting (*Figure 2*). If it were not for this photoperiodic control, late-planted rice would have its growing period extended into the dry season and run the risk of a water shortage before maturity.

High-yielding miracle varieties have been bred to be insensitive to photoperiod variations in the tropics (Jackson *et al.*, 1969). This shortens the growing period and makes the varieties adaptable to carefully managed irrigation schemes where rice can be planted at any season of the year. However, many growers complain that such varieties do not adapt well to the natural trend of the wet and dry seasons when grown under rain-fed conditions.

The photoperiodic response of rice has as many complexities as there are varieties (Best, 1961; Lamin and Vergara, 1968). Although most varieties are short-day plants, many are nearly day-neutral and some appear to respond to long photoperiods. Sensitivity at different stages of development varies from variety to variety. Light intensity appears to have a strong influence on the sensitivity of many varieties to the dark period. This sensitivity ranges from 0.11–8.60 × 10^{-6} cal cm^{-2} min^{-1} in the morning to 1.15–50.17 × 10^{-6} cal cm^{-2} min^{-1} in the evening. It is obvious that haze, cloud and fog during the twilight period before sunrise or after sunset affect the dark-period light intensity and therefore the effective photoperiod and resulting rate of development of rice.

3.3 Temperature

Temperature has a subtle and, in some respects, contradictory influence on the development, growth, and yield of rice. Each development stage and each growth process responds differently to the same temperature condition (Ishizuka *et al.*, 1973). While the plant is germinating and in the seedling stage it is the water temperature which is important since the growing-point is under water. At later stages when the growing-point and seed-bearing parts of the plant are well above water, both the day-time and night-time air temperatures play important roles. To complicate the picture each of the many hundreds of varieties has its own characteristic responses making it suitable for the local climatic conditions (*Figure 3*).

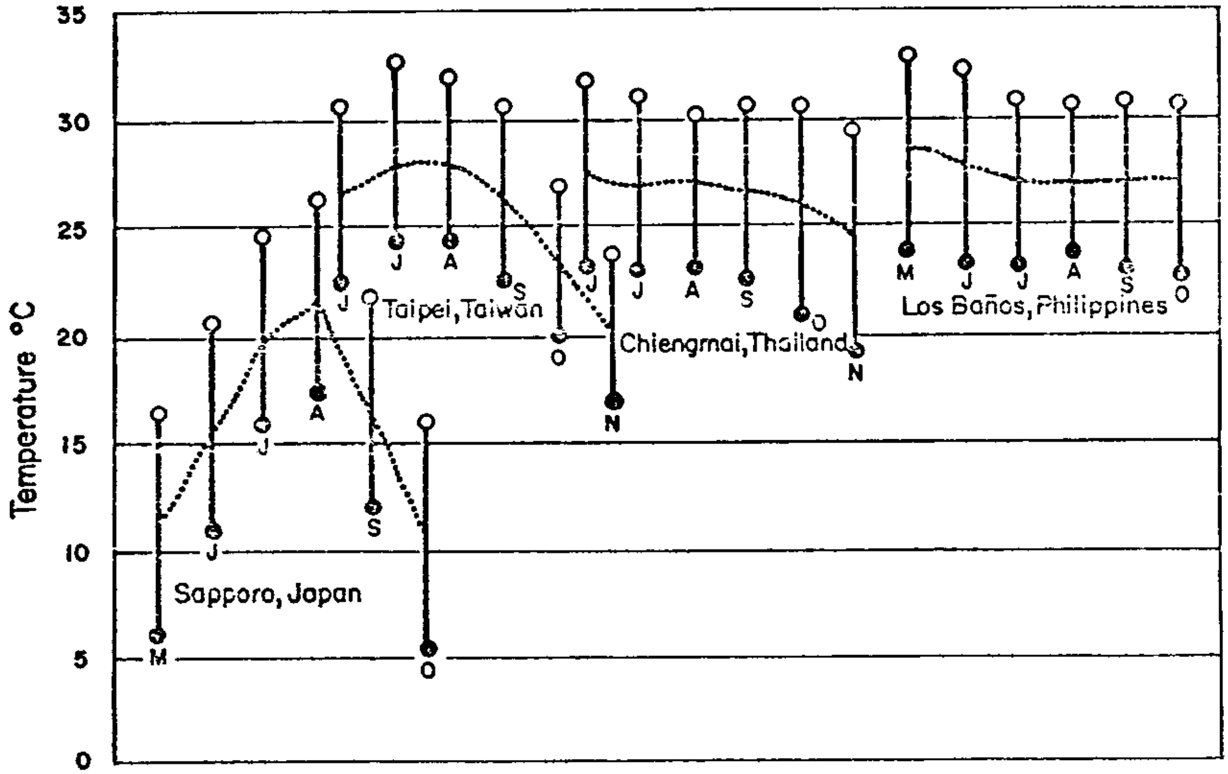

Figure 3—Mean temperatures and temperature ranges during the main rice-growing months at four locations in Asia (Anonymous, 1970*a*).

Being a tropical or subtropical plant, rice generally requires high temperatures, above 20°C, but not above 35 to 40°C (Nuttonson, 1965). The optimum appears to be near 30°C for the day-time maxima and near 20°C for the night-time minima (Owen, 1972*c*).

Low temperature slows the rate of germination below the desirable span of six days. Germination will continue in some varieties at temperatures as low as 13°C but the time to complete germination may be ten days or longer. During seedling growth, low temperature promotes faster root development and better penetration into the soil. On the other hand, low temperature does not favour prolific root development. Net photosynthesis has been observed in some seedlings at temperatures as low as 5°C. The tillering rate is inhibited by low temperature (Owen, 1972*b*) but the period for tillering is prolonged so that often the net result is more tillers and more panicles than at higher temperature. During the period of internode elongation, low temperature leads to short culms, partial emergence of the panicle and minimal leaf emergence; all of which result in low rates of photosynthesis, partial sterility and, eventually, problems at harvesting and threshing time (Satake, 1969). In contrast to these deleterious effects before ripening, low temperature during ripening prolongs the period, reduces respiration, and helps maintain green leaves on the plant, all of which contribute to the high accumulation of carbohydrate in the seed. Unfortunately, low temperature during the final ripening stage leads to excessive shattering of grain during harvest and transportation of the sheaf, resulting in high grain losses before threshing.

High temperatures of 35 to 40°C or more exhibit many of the effects of low temperature although undoubtedly biochemical reactions are much different. Germination is halted because of the high respiration rate. Root development is slow. Tiller numbers increase and rate of development is retarded. Panicle development is almost completely inhibited and pollen germination is slow. During the ripening period, high temperature produces an undesirable chalky appearance in the rice kernel and increases the bran thickness.

At the optimum temperature (near 30°C) seed germination takes place in five to six days (Hall, 1966*a, b, c*).

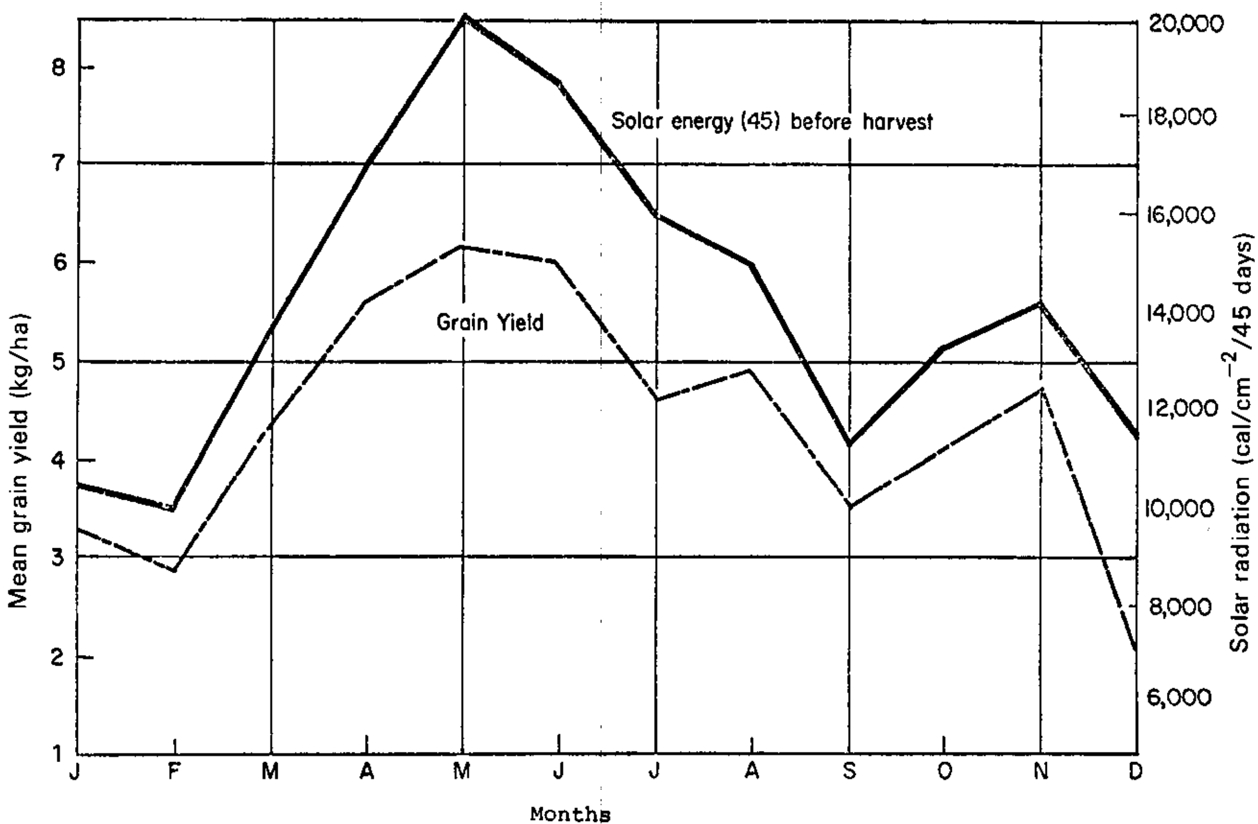

Figure 4—Mean grain yield of IR8 for three levels of nitrogen (0, 30, 90 kg/ha) and three spacings (15 × 15, 25 × 25, 35 × 35 cm) plotted against solar radiation totals during the last 45 days before harvest (Anonymous, 1970*a*).

In the seedling stage, shoot elongation is most rapid and dry matter reaches a maximum. The final number of tillers and panicles may not be a maximum, but since spikelet number and tiller number are inversely related, the result is maximum yield. Plant height is greatest at a somewhat lower optimum temperature of 25°C while the rate of leaf emergence increases with temperature up to about 35°C. At the ripening stage, yield is inversely proportional to temperature under uniform sunlight. On the other hand, if temperature is near the optimum, as it is in the humid tropics, then yield appears to be proportional to temperature, but this is only apparent, as both yield and temperature are influenced in the same direction by solar radiation intensity.

Attempts to characterize the rate of development of rice by temperature summation equations appear to have met with little success. This is undoubtedly due to the complex influence and interaction with photoperiod, water temperature and day and night air temperature on the rate of development of rice during different periods of development (Chang and Vergara, 1971). Apparently no attempt has been made to apply to rice development the biometeorological time scale which has been used successfully to predict the rate of development of wheat from day and night temperatures and photoperiod (Amores-Vergara, 1973; Robertson, 1968, 1973; Williams, 1974).

3.4 **Solar radiation**

The importance of sunshine in helping to produce high yields in rice was recognized as early as the late 1940s. More recently, intensive research at IRRI has demonstrated that the quantity of solar radiation has a profound influence on rice yield (*Figures 4 and 5*), particularly during the last 30 to 45 days of the ripening period (Moomaw *et al.*, 1967; Rao and Deb, 1974). The effect is most pronounced when water, temperature and nitrogenous nutrients are not limiting. Some varieties are more responsive to solar radiation than others. Low temperatures accompanied by bright sunshine are most desirable since the ripening period is prolonged, resulting in a greater accumulation of total radiation and therefore carbohydrate during this critical period.

Since most rain-fed rice is grown during the rainy season, solar energy is frequently limiting, resulting in minimum yields. Only where irrigation is possible can rice be planted at a date which will result in the ripening-period coinciding with a period of high global solar radiation during the dry season (De Datta and Zarate, 1970).

The intensity of solar radiation is one of the main environmental factors used in a recent mathematical model for calculating potential rice yields. It was assumed that the rice plants were non-lodging and non-photosensitive and that temperature and water were not limiting. Calculated potential yields agreed well with actual yields produced on carefully managed plots at several different latitudes ranging from the Equator to 43°N (van Ittersum, 1971).

3.5 **Wind**

Wind is normally an unimportant factor in rice production. A light wind is said to be beneficial as it stirs the air and transports CO_2 to the leaf canopy. Occasionally, however, very strong winds do occur, such as during typhoons, and serious damage results. During pollination strong winds may induce sterility and increase the number of abortive endosperms. Ripening plants may suffer severe grain shattering. Lodged plants are more protected from these deleterious effects of strong winds. Certain leaf diseases may be spread more rapidly and farther afield by strong winds (Ling, 1972; Ou, 1973).

3.6 **Atmospheric water vapour**

Rice grown in the humid tropics is subjected to unusual stresses by the continuously high water-vapour pressure of the atmosphere. At Los Baños in the Philippines, for example, the average vapour pressure is about 28 mb and the vapour-pressure deficit (VPD) about 7 mb. At night-time and during prolonged rainy periods the VPD often falls to zero. Such humid conditions are favourable for the development and spread of many fungal and bacterial diseases (Ou, 1973). As these moist conditions must be accepted in the humid tropics, the only solution is to breed and select rice varieties which are resistant to local diseases and to encourage farm-management practices which will keep the occurrence and spread of disease to a minimum.

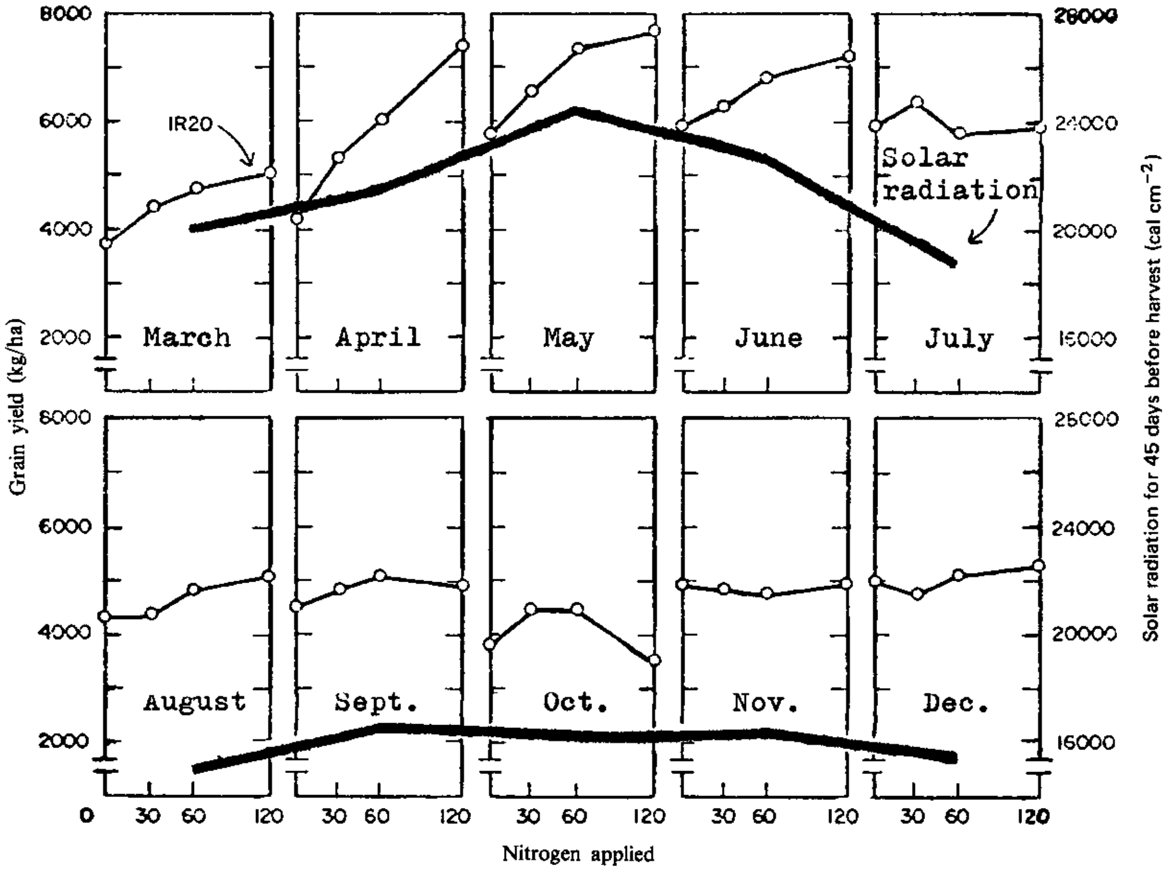

Figure 5—Nitrogen response of IR20 by harvest month plotted against solar radiation total for 45 days before harvest. Date-of-planting experiment, IRRI, 1969 (Anonymous, 1970*b*).

High atmospheric water-vapour content is responsible for a great deal of rice spoilage in the humid tropics. Rice is harvested with a water content between 20 and 35 per cent (Anonymous, 1970*b*). When it is air-dried in a humid tropical climate such as that of Los Baños, the equilibrium moisture content of the grain is between 16 and 20 per cent. For safe, prolonged storage the moisture content must be reduced to between 13 and 14 per cent and for optimum milling to 11 per cent. Farmers dry their rice for home use by spreading a small amount in a thin layer on a dry surface exposed to bright sunshine for several hours. For commercial purposes, however, special grain driers are required which will handle several metric tons per day.

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CHAPTER 4

FORECASTING THE YIELD OF PADDY RICE

4.1 Importance

Forecasting the yield of agricultural crops before harvest is of prime importance to a nation with a well-organized food and agricultural economy (Robertson, 1974a), for the following reasons: advanced planning for food and other relief measures in areas with impending crop failure; providing information about areas with surplus foods to assist in grain-redistribution planning within the country; planning for food purchases (or sales) in case of expected shortage; aiding with decisions regarding withdrawals and additions to national food reserves.

4.2 Methods

Two procedures may be used to predict crop production at harvest time. The most common one is for some central agency to gather crop-condition reports from observers throughout the country. These observers are usually field-men in local areas: research agronomists, agricultural extension workers, staff at local agricultural schools, and other professional agricultural personnel working in the area. The system has some weaknesses. Observations are subjective and, depending on local and recent weather conditions, may be biased. There is sometimes a tendency to over-emphasize the results of impending flood and drought damage. Communication problems may delay the transmission of reports from several days to a few weeks, thus lessening their value for forecasting production and for immediate decision-making. Crop-condition reports are usually given in subjective terms and it is difficult to translate these into numerical terms of crop production.

To overcome the latter problems, the second method involves the use of current and immediate-past weather data. Weather-based yield predictions can be made throughout the life-cycle of the crop. The justification for such early-yield estimates is based on the fact that at any given moment during the life of a crop it has a certain "inertia" which may carry it, with varying degrees of success, to maturity and fruition. This inertia is determined by the state of the crop and the available store of soil moisture and nutrient at the given moment. These three factors all depend to some degree on the immediate-past weather up to the moment of the estimate. The state or health of the crop is determined by the past temperature, radiation and soil moisture and possibily other environmental conditions (Baier, 1973; Robertson, 1974*b*). The stored moisture depends on the balance between rainfall and actual evapotranspiration (Baier and Robertson, 1968). The stored soil nutrients depend on soil moisture, soil temperature and leaching by heavy rains (Campbell *et al.*, 1973). This inertia will carry the crop to maturity given average climatic conditions for the balance of the life-cycle of the crop (Robertson, 1974*a*). Using climatic probabilities for the remainder of the life-cycle, the probable changes in the crop's inertia can be indicated and a probabilistic yield estimate made. The degree of accuracy of such estimates is usually much better than that which could be obtained from climatological probabilities alone and are more timely than subjective crop-condition reports. In fact, they probably provide more lead-time over the system of crop-condition reporting for decision-making than can be achieved by the use of the general type of long-range weather forecasts currently available. Of course, estimates made early in the life-cycle of the crop cannot be as accurate as those made at later stages since the crop inertia in early stages is often altered by the development of soil-moisture deficiencies, by unfavourable temperatures and by anomalies in other environmental conditions. On the other hand, where conditions become more favourable as the life-cycle of the crop advances, it is possible for the crop to gain inertia in regard to final yield production.

Information about future weather from a reliable weather forecast could be used to advantage partially to replace climatological probabilities for determining future changes in the current inertia of the crop. However, the improved accuracy achieved is maximum for forecasts for the immediate future (one to three days) and decreases to near zero for attempted forecasts beyond about 30 days. In fact, a more reliable and longer lead-time for decision-making can be gained by making use of real-time weather-based yield estimates than by the extension of the lead with long-range weather forecasts.

Useful crop-weather models should be capable of showing changes in the inertia of the crop on almost a real-time basis. Most countries have an existing meteorological observing network of synoptic stations. These stations take observations at six-hour intervals and transmission to one or more national centres is almost immediate. The prime usage of synoptic weather reports is for making weather forecasts. However, the reports are also suitable for crop-production estimates and, given suitable crop-weather models and modern electronic computing devices, weather-based crop conditions and yield estimates can be made on a real-time basis at frequent intervals throughout the life-cycle of the crop.

Some of the disadvantages of the weather-based estimates are: possibility of imperfect and incomplete mathematical relationships leading to large errors in seasons with anomalous weather; inability to account for the influence of insects and epidemics of diseases; and the inadequacy of weather-station density.

Probably the best technique is a combination of the crop-condition reporting system and the weather-based estimating system. Information from both systems is cross-checked to avoid undue errors or misleading interpretations. In some countries weather data are used to provide a warning of untimely conditions which may lead to anomalous crop yields. When such conditions are indicated, field crews are alerted to take special crop surveys and transmit results quickly by special techniques.

Although considerable effort has been expended on developing models for making routine, real-time weather-based estimates of wheat yield (cf. WMO, 1974), it appears that only a limited amount of research has been undertaken along similar lines for estimations of rice yield and production (van Ittersum, 1971).

4.3 **Models for rice yield in India**

Research carried out in India in this regard should be mentioned (Das and Madnani, 1971). The technique employed is a common one. Multiple-regression analysis and long-term records of yields and weather data were used to establish relationships between yield and certain weather factors at specific times in the life-cycle of the rice crop.

A long series of data from 1906 to 1966 was used to establish regression equations for Madhya Maharashtra subdivisions of Maharashtra State (Das and Madnani, 1971). The following equations were developed. For estimates made in the first week of August:

$$\hat{x}_1 = 365 + 33.7x_2$$

For estimates made in the first week of September:

$$\hat{x}_1 = 471 + 33.7x_2 - 49.7x_3$$

For the final estimate made in the first week of October:

$$\hat{x}_1 = 430 + 33.7x_2 - 49.7x_3 + 9.65x_4$$

where $\hat{x}_1$ is the expected yield;
x_2 is the number of rainy days in July;
x_3 is the number of occasions of drought in August;
x_4 is the number of rainy days during the last half of September.

Rainy days are those with 2.5 mm or more of rainfall in 24 hours. Occasions with drought in August are determined from the number of consecutive days with less than 2.5 mm of rain and coded as follows:

7 days	Code 1
8 to 14 days	Code 3
15 to 21 days	Code 6
22 days or more	Code 10

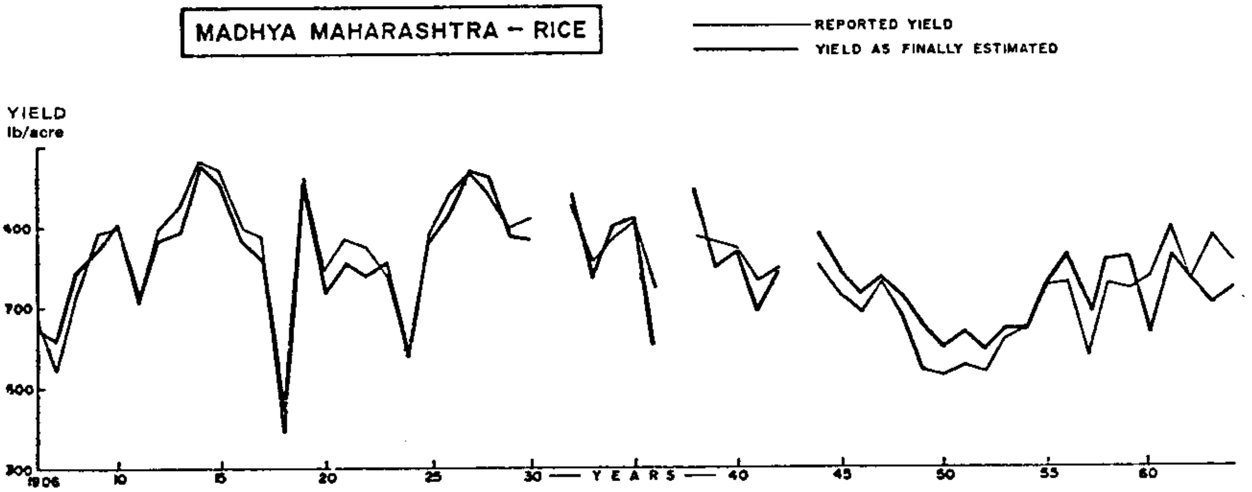

Figure 6—Comparison of estimated and reported yields of rice in Madhya Maharashtra area (Das and Madnani, 1971).

The multiple-correlation coefficient for the complete equation (October) was nearly 0.90, indicating that the regression accounted for 81 per cent of the anual yield variations. The standard error of estimation was 51 kg/ha. Similar data were not presented for August and September, but encouraging results are indicated (*Figures 6* and 7).

Similar techniques were used in developing equations for other rice-growing areas of India, such as the States of Tamilnadu, Kerala, Karnataka, Coastal Andhra Pradesh, the sub-Himalayan portion of West Bengal, Konkan, Gangetic West Bengal and Bihar.

In developing these relationships it was found that different weather elements were important as predictors for different areas. In addition to the elements used for Madhya Maharashtra, the following have also been found important in some areas during certain periods of the life-cycle of the crop:

Rainfall amount;
Log of rainfall amount;
Mean temperature;
Square of mean temperature;

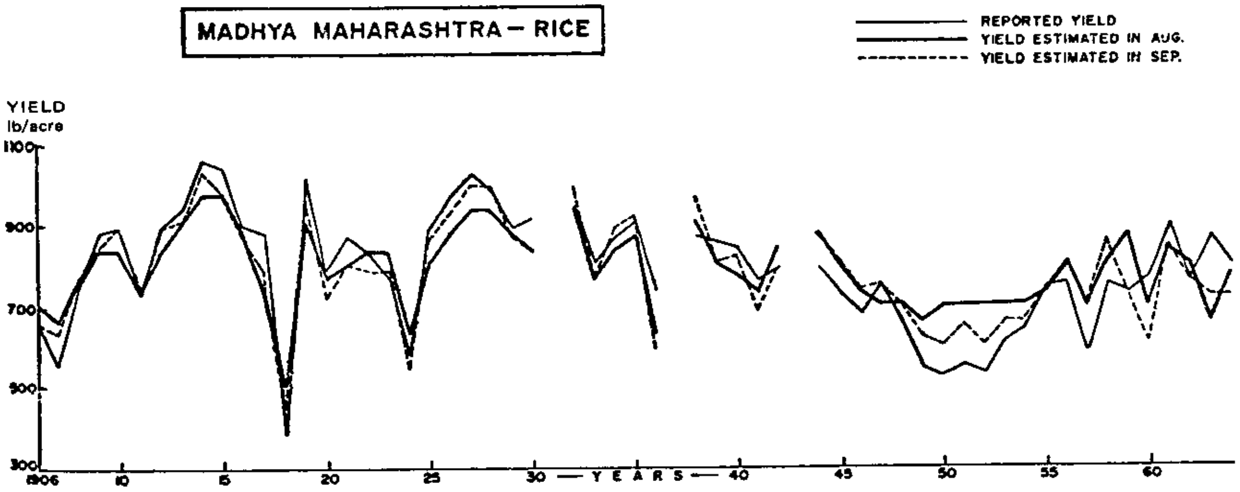

Figure 7—Comparison of yield estimates made in August and in September with reported yields (Das and Madnani, 1971).

Mean cloudiness;
Rainfalls in excess of certain large amounts;
Technological trend.

Elements which were not significant as yield predictors were eliminated by means of a *t*-test applied to the regression coefficient. Significance at least at the five per cent level was required for acceptance.

Usually the elements employed are monthly or weekly averages. It appears that no attempt has been made to develop a national relationship for all areas by associating the weather elements with phenological periods instead of calendar months (Baier, 1973). This would require a soil factor as a variable, but this extra variable would be more than offset by the large gain in degrees of freedom and the possibility of extending the range of the independent variables. These improvements should make the final equation more reliable over a wider range of anomalous weather conditions.

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CHAPTER 5

IRRIGATION

5.1 Effective rainfall

In most climates where rice is grown, rainfall is more than sufficient at certain times and varying amounts may be lost due to runoff or deep percolation. At other times rainfall may be so light in individual showers as to be ineffective.

Irrigation agronomists have devised many techniques for estimating "effective rainfall". Kung (1971) described some of these and the following examples taken from his review are typical of several of the techniques in use.

"*For paddy (submerged) in Japan*

1. First, a "standard" year is fixed in which the amount of rainfall during the irrigation period is so small that it occurs once in every 10–20 years (average 15 years).
2. Daily readings are used as a basis and the millimetre as the unit.
3. A daily amount less than 5 mm is disregarded.
4. A daily amount of more than 50 to 80 mm (depending on the conditions of the paddy field in different localities) is assumed to cause overflow of the earth bank and is also considered non-effective. Therefore, daily rainfall from 50 to 80 mm is taken as 50 mm.

"It is assumed that small amounts of rainfall water are intercepted and then evaporated before turning into soil moisture for transpiration by the plants. Heavy and intensive rainfalls will be lost, depending upon the intake rate and storage capacity of the soil in the root zone of the crop. Surface runoff is likely to occur. In the case of rice, when a paddy field is full of water, any additional water from rainfall will run off over the earth bank. Therefore, the amount of rainfall below or over a certain limit is considered as non-effective."

The success of such techniques depends on the fact that they have been developed for specific areas with known soil and climatic characteristics. There is a need, however, for a more objective and universal technique which would work in any climate and for given specific soil-water characteristics. The meteorological water-budget technique works well for this purpose (Robertson, 1970). It requires observations of daily rainfall and a daily estimate or measurement of potential evapotranspiration.

5.2 Evapotranspiration

Under flooded conditions a rice crop will have ample water for the evapotranspiration process. Because of this fact, transpiration from the growing rice and evaporation from the water surface will approximate the potential evapotranspiration rate. In some cases, depending on the size of the paddy, the crop roughness and the aridity of the surrounding area, a rice crop may evapotranspire more than the potential amount (Evans, 1971).

Asuncion (1971) compared evapotranspiration from a controlled rice paddy with evaporation both from a sunken pan and from a Class A pan for three seasons in the Philippines: 1966 wet season, 1967 dry season and 1968 dry season. Data for the 1969 wet season were discarded as they appeared faulty. For the growing period of the rice during the three seasons the average daily actual evapotranspiration, sunken pan evaporation and Class A pan evaporation were, respectively, 5.6, 4.6 and 6.1 mm. The average ratio of actual evapotranspiration to sunken pan evaporation was 1.20 and to the Class A pan evaporation was 0.91. The correlation coefficients for daily values of actual evapotranspiration with both pans were nearly the same, about 0.72.

Evans (1971) made a similar comparison for Australia. His measurements were taken in one growing season during a 25-day period when the crop had reached full height whereas Asuncion (1971) used data for the growing seasons over a three-year period. For the Australian experiment the ratio of actual evapotranspiration to class A pan evaporation averaged about 0.98, but varied from 0.77 to 1.47, depending on the roughness length of the crop. The correlation coefficient for the 25 cases was 0.91.

The higher average ratio for the Australian experiment is probably due to the fact that all measurements were made on rice at maximum height. Also the Class A pan was some 15 km from the rice lysimeter so that distance may also have caused some of the variability in the daily ratios. In the Philippines the lysimeter and the pans were separated by only 1.5 km.

Asuncion (1971) also had evaporation data from a paddy-type lysimeter with no crop. For the same three reasons as previously mentioned, he found the ratio of evaporation from open water in a paddy with no crop to evaporation from the Class A pan to be 0.61.

It would appear, therefore, that the ratio of paddy evapotranspiration to Class A pan evapotranspiration increases from about 0.6 before rice is transplanted to near 1.0 as the rice progresses towards maximum height. These limits might serve as a guide for estimating paddy evapotranspiration from measurements of Class A pan evaporation.

5.3 **Water-budget calculations**

General methodology

It is sometimes necessary to make an estimate of the water requirements of rice under field operations with known soil and weather conditions. Such estimates have at least three specific uses: to determine the adaptability of rice to the specific water régime of a given area; to produce zonation maps showing suitable areas for rice culture; and to estimate the irrigation requirements of rice for operational purposes.

For these purposes it is possible to make a budget accounting of water losses and gains and to determine objectively water surpluses or deficits if any, thus indicating the size of the respective drainage or irrigation systems required, or the suitability of a certain climate for rice production. The following items contribute to the gain: rainfall (P), irrigation (I), and surface water inflow (G); while the following are responsible for the losses: evapotranspiration (E), percolation losses (U), runoff (Q), and soil water-storage changes (ΔW). These factors may be equated as follows:

$$P + I + G = E + U + Q + \Delta W$$

It is necessary to evaluate the water-holding capacity of the soil at saturation. Under flooded conditions in the rice paddy evaportranspiration will be approximately equal to the potential evapotranspiration rate which can be estimated as about 85 per cent of the Class A pan evaporation (Asuncion, 1971). The object of such a soil-water budgeting system is to calculate the amount of water remaining in storage at the end of each day. This storage will be the sum of the total water at soil saturation plus the depth of flood-water in the paddy. It may be desirable to vary the depth of flood-water during the growing season as the crop progresses towards maturity. One bit of supplementary information from the budget calculations is the water deficit, i.e. the daily amount by which the total stored water fails to meet the desirable depth in the paddy. The accumulation of these daily deficits gives an indication of the total amount of irrigation water required. It is difficult in many circumstances to maintain water at a fixed level in the paddy and may be necessary therefore to allow the water level to fluctuate, say between zero and 10 cm depth. In such a case a deficit would occur if the water level fell below zero cm while a surplus available for runoff would occur if the depth exceeded 10 cm.

Practical example

Calculations are shown for hypothetical monthly conditions in *Table III*. It was assumed that Class A pan evaporation and rainfall measurements were available, and that the paddy soils held 200 mm of water at saturation; it was near the beginning of the rainy season and the soil at the beginning of the month contained only 150 mm of water, as yet not saturated; also, flooding between zero and 100 mm of water was desirable.

The loss due to deep percolation must be determined experimentally. In the example, the percolation rate was high early in the month when the groundwater level was deep. Later in the month, as rains became heavier and the groundwater level rose, the deep percolation rate decreased from 5 to 3 mm per day.

TABLE III

Sample daily soil water budget calculation for a rice paddy (mm)

(*After Robertson, 1970*)

Date	P	I	G	*Total*	E	U	*Total*	ΔW	S	D	Q
(*From previous day*)									150		
1	0		0	0	7	5	12	−12	138		
2	20			20	5	5	10	10	148		
3	50			50	2	5	7	43	191		
4	39			39	3	5	8	31	200		22
5	15			15	5	5	10	5	200		5
6	5			5	6	5	11	−6	194		
7	0			0	7	5	12	−12	182		
8	0			0	7	5	12	−12	170		
9	0			0	8	5	13	−13	157		
10	10			10	6	5	11	−1	156		
11	5			5	6	5	11	−6	150		
12	0			0	7	5	12	−12	138		
13	0			0	6	5	11	−11	127		
14	0			0	6	5	11	−11	116		
15	0			0	7	5	12	−12	104		
16	5			5	5	5	10	−5	99	1	
17	0			0	6	5	11	−11	88	12	
18	0	75		75	5	5	10	65	153		
19	5			5	6	5	11	−6	147		
20	8			8	6	5	11	−3	144		
21	1			1	5	5	10	−9	135		
22	0			0	6	5	11	−11	124		
23	30			30	4	5	9	21	145		
24	45			45	3	5	8	37	182		
25	40			40	2	5	7	33	200		15
26	33			33	2	4	6	27	200		27
27	50			50	1	4	5	45	200		45
28	47			47	2	4	6	41	200		41
29	10			10	4	3	7	3	200		3
30	35			35	3	3	6	29	200		29
31	28			28	2	3	5	23	200		23
Total	481	75			150	146				13	210

NOTE: P—precipitation; I—irrigation amount; G—surface inflow; E—potential evapotranspiration; U—infiltration; ΔW—soil-water storage change; S—soil-water storage; D—daily deficit; Q—surplus water (assumed runoff).

Rains were light and infrequent for the first 22 days of the month. In fact more water was lost by evapotranspiration and deep percolation than was received in the form of rain. This resulted in the stored water in the paddy decreasing to below the lower critical level (100 mm) on the 16th. Irrigation water, amounting to 75 mm, was added on the 18th to prevent the water level from going too far below the critical level. This was sufficient to last until the 22nd after which heavy rains occurred and filled the paddy to 200 mm—its maximum capacity. Thereafter rain water in excess of the evapotranspiration and deep-percolation requirements was lost by runoff. Subtracting the total runoff for the month, 210 mm, from the total rainfall of 481 mm plus the irrigation water added, 75 mm, gives an estimate of the effective rainfall, (481 + 75 − 210) = 346 mm. In this case, minor rainfalls were considered relatively as important as heavier rains. It was assumed that rain which wet the foliage consumed energy for evaporation and that this decreased the amount of energy available for transpiration, which itself in turn was reproduced and thus saved an equivalent amount of soil water. Therefore every small rainfall made a contribution to the water budget in proportion to its size.

The amount of irrigation, 75 mm, was arbitrarily determined. The paddy could have taken 112 mm at the time of irrigation. However, it was felt that rains might come within a few days and that a partial irrigation of only 75 mm would be sufficient. As the record shows, 50 mm would have been sufficient.

Applications

Such a budgeting technique can be used with daily historical data to determine several of the climate characteristics of the area. Using daily data for 10 to 25 years it is possible to determine the statistical distribution of surplus water or water deficit for monthly, weekly or other periods. *Tables IV* and *V* illustrate the probabilities of monthly irrigation requirements and water surpluses, respectively, at los Baños, Philippines (lat.

TABLE IV

The percentage probability (P) of requiring more than the amount of indicated irrigation water (mm) to supplement the natural rainfall on a monthly and annual basis at the University of the Philippines College of Agriculture, Los Baños, for the period 1959 to 1968. (It is assumed that the soil holds 50 mm of readily available water.)

(*After Robertson, 1970*)

P (%)	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Annual*
99	0	36	69	94	0								284
90	5	41	94	119	13								396
80	20	69	107	132	30								442
70	28	76	114	142	46								478
60	38	84	119	145	56						0		508
50	46	89	127	155	66						5		533
40	53	94	132	163	79					0	8	0	559
30	61	102	140	168	89			0	0	3	13	8	589
20	71	109	147	178	104	0		5		8	15	15	625
10	86	119	157	188	122	13	0	13		13	23	28	673
1	117	142	185	216	168	41	5	33	0	25	38	56	785

NOTE: Another interpretation of data in this table may be given by a few examples: in February the irrigation water requirement is greater than 102 mm in 30 years out of 100 or in 3 out of 10; similarly, the annual irrigation water requirement is greater than 785 mm once in 100 years whereas it is greater than 284 mm in 99 out of 100 years.

TABLE V

The percentage probability (P) of the monthly and annual surplus water being greater than the indicated amount (mm). Soil water storage is assumed to be 50 mm of readily available water and evapotranspiration is assumed to be at the potential rate. Based on data from the University of the Philippines College of Agriculture, Los Baños, for the period 1959 to 1968.

(*After Robertson, 1970*)

P (%)	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Annual*
99	*	*	*	*	0	0	8	18	0	0	8	0	330
90					0	8	33	51	23	0	38	0	559
80					0	23	48	69	46	5	64	0	686
70					3	41	69	89	74	13	86	0	782
60					8	61	86	109	99	23	109	3	869
50					20	89	107	124	130	41	137	10	970
40					38	119	130	147	175	58	165	20	1 069
30					69	160	157	168	224	89	203	38	1 181
20					119	218	188	203	290	137	254	69	1 321
10					224	325	246	254	406	224	330	142	1 524
5					340	432	297	300	526	323	406	221	1 727
1					660	686	422	406	790	559	584	457	2 134

NOTE: A cube-root transformation was used to normalize the distribution.
* Insufficient data for evaluation.

14° 10′ N) (Robertson, 1970). Such information is useful for planning purposes in connexion with the design of irrigation and drainage systems.

Using the accumulation of stored water in the soil after a dry season, the beginning of the wet season can be defined and calculated by the budget technique and its statistical distribution determined by using several years of data. *Table VI* shows such probability distributions, not only for the beginning of the wet period, but also for its end and duration. The criterion for the beginning of the wet season is that it commences after 50 mm of water have accumulated in the soil according to the budget calculations. Similarly the wet season ends when soil water becomes less than 50 mm (Robertson, 1970).

TABLE VI

The percentage probability of the beginning, ending and duration of the wet season being equal to or earlier (less than) the dates (value) shown. Based on data from the University of the Philippines College of Agriculture, Los Baños.

(*After Robertson, 1970*)

Probability (%)	*Date*		*Duration* (*days*)
	Beginning	*Ending*	
1	Apr. 11	Nov. 24	176
10	Apr. 26	Dec. 17	204
20	May 2	Dec. 26	215
30	May 7	Jan. 2	224
40	May 11	Jan. 8	231
50	May 14	Jan. 14	238
60	May 18	Jan. 19	245
70	May 22	Jan. 25	253
80	May 26	Feb. 1	261
90	June 2	Feb. 10	273
99	June 17	March 5	300

In the illustration (*Table VI*) the probability that the wet season will be 220 days or less is about 25 per cent (or that it will be more than 220 days is 75 per cent), indicating that there is better than an even chance of growing two successive rice crops (110 days each). This type of information is useful to agronomists for planning dates of seeding and of harvesting new varieties, and for developing multiple-cropping systems.

This technique could be used for calculating other soil-water or rainfall characteristics such as: probabilities of the number of days that the soil is wet (or dry) during a given period; the probabilities of runs of wet or dry periods of various durations and so forth. Analyses for several stations could be used for mapping such derived climatic characteristics for rice-zonation purposes. Unfortunately such techniques have not been applied in practice for humid areas, so that examples are not available.

CHAPTER 6

CLIMATIC ZONATION FOR RICE IN MONSOON REGIONS

6.1 Information source

In preparing this review the only rice-zonation map encountered was one published in a report prepared by a working group* for the International Rice Research Institute (Anonymous, 1974).

The section of this report dealing with the climatic zones of South-East Asia suitable for paddy rice (one or two crops) without irrigation has been reproduced here almost verbatim for the report†.

6.2 Rainfall patterns in South-East Asia

Rainfall in South-East Asia is determined by regional as well as local phenomena. The most important are:

(*a*) The movement of the equatorial low pressure belt, following the solar path;
(*b*) The occurrence of monsoons, created by the heating and cooling of large land masses;
(*c*) Orographic lifting;
(*d*) Diurnal heating of land areas;
(*e*) Cyclone formation.

In general a fair amount of data on rainfall is available for most of the South-East Asian countries. However, other macroclimatic parameters such as evaporation, temperature, relative humidity, wind speed and particularly solar radiation are seldom recorded. Therefore these data could not be used to evaluate evapotranspiration. The climatic zones selected are thus entirely based on rainful as the dominant factor, and therefore more or less follow the rainfall pattern. Refinements should be made once certain zones have been chosen for further study.

6.3 Climatic zones

By grouping together available information on rainfall profiles, a number of the most prominent rainfall patterns were selected. Some countries such as Indonesia and the Philippines have carried out this type of study (e.g., based on more than 4 000 sites in Indonesia, around 150 dominant rainfall profiles were selected). The following general criteria have been used as the basis for the selection of major climatic zones for this study:

(*a*) Monthly rainfall. An arbitrary boundary was set at 200 mm. This amount is based on two assumptions:
  (i) Losses due to evapotranspiration, although variable over the year, generally amount to around 100 mm per month;
  (ii) Losses due to percolation and seepage, although variable depending on soil characteristics, are generally set at around 100 mm per month.
(*b*) Number of months with 200 mm or more of rainfall. An arbitrary boundary was set at five to nine consecutive wet months. If there are fewer than five consecutive wet months the possibilities of growing two crops are limited. If there are more than nine consecutive wet months the South-East Asian farmer is most likely to grow two crops of puddled rice. Based on these two criteria, the following zones were selected (*Table VII, Figures 8a and 8b*).

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* Working Group on the Establishment of South-East Asian Cropping Systems Test Sites. IRRI, Los Baños, Philippines. October 29 to November 10, 1973. Members: J. K. Coulter, J. F. Derting, L. R. Oldeman, M. M. Obradovich, T. B. Slattery.

† With the kind permission of Dr. N. C. Brady, Director, IRRI.

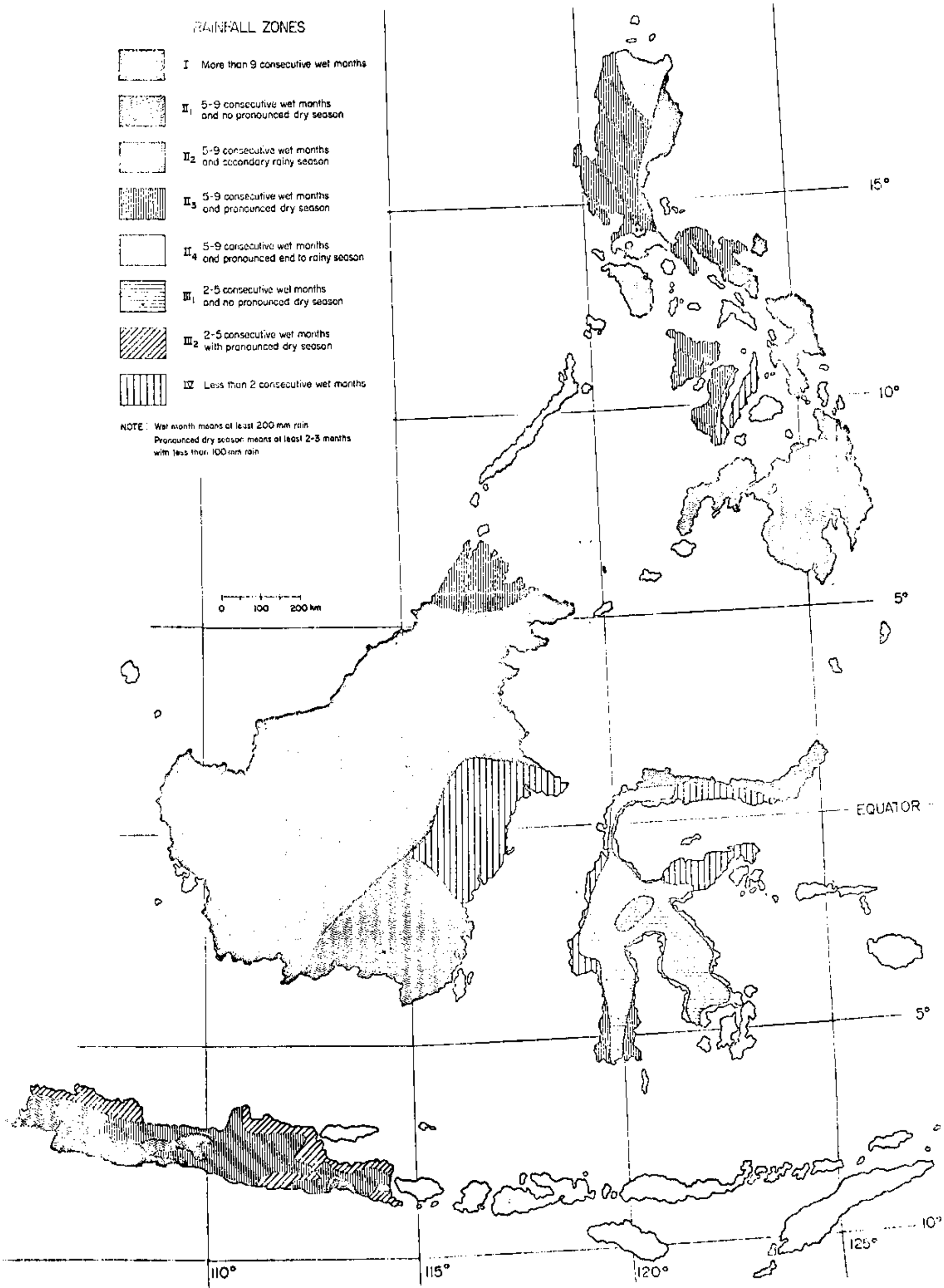

Figure 8*a*.—Rainfall zones in South-East Asia (Anonymous, 1974).

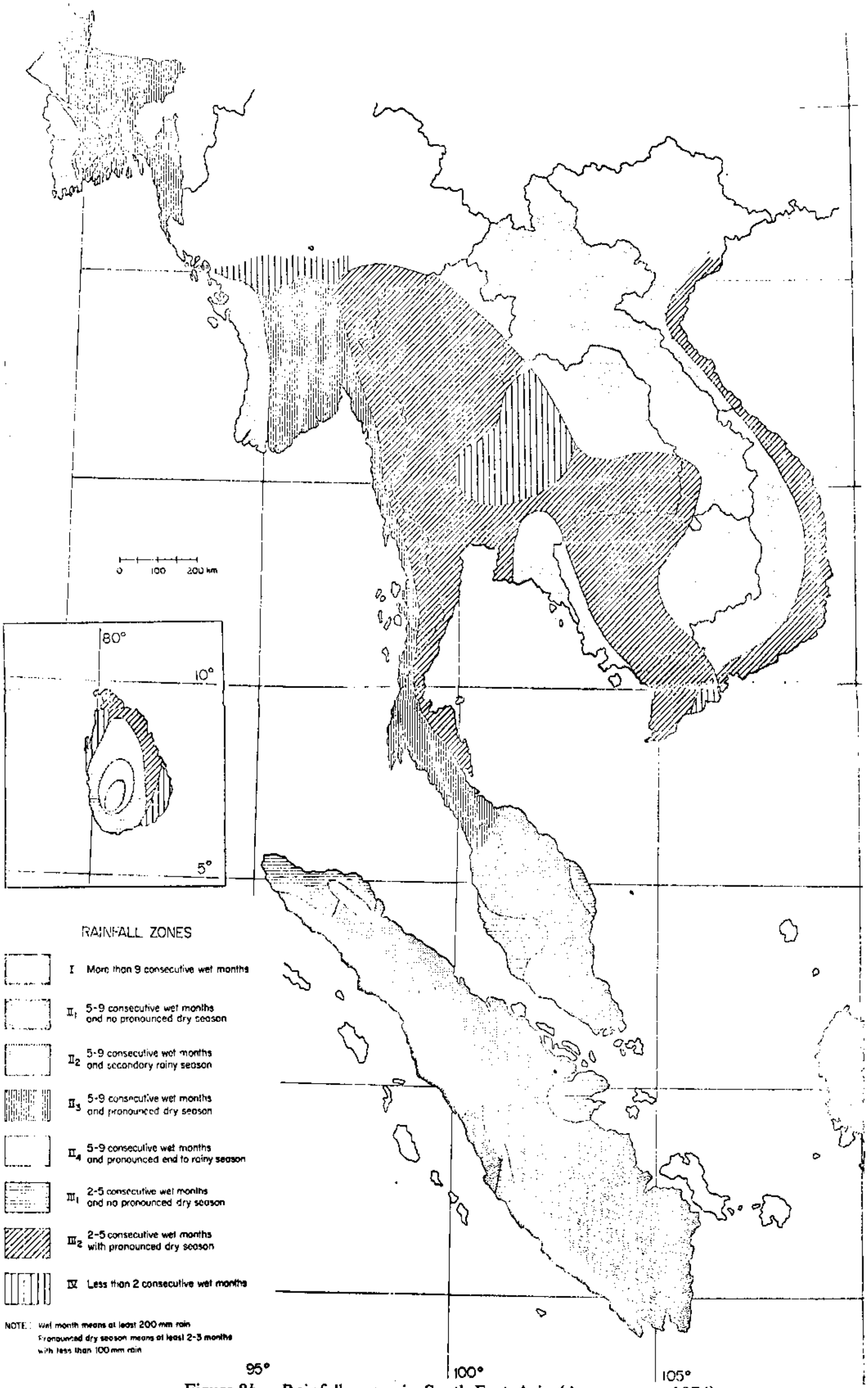

Figure 8*b*.—Rainfall zones in South-East Asia (Anonymous, 1974).

Zone 1. Areas with more than nine consecutive wet months with more than 200 mm of rainfall per month (*Figure 9A*). This zone includes the major part of Kalimantan and east Malaysia, central Sumatra, the north-west coast of Sumatra, and isolated spots in Java, primarily the south-western part. In addition, there are isolated spots near the mountains. Eastern Mindanao, Visayas and Luzon in the Philippines also come into this group.

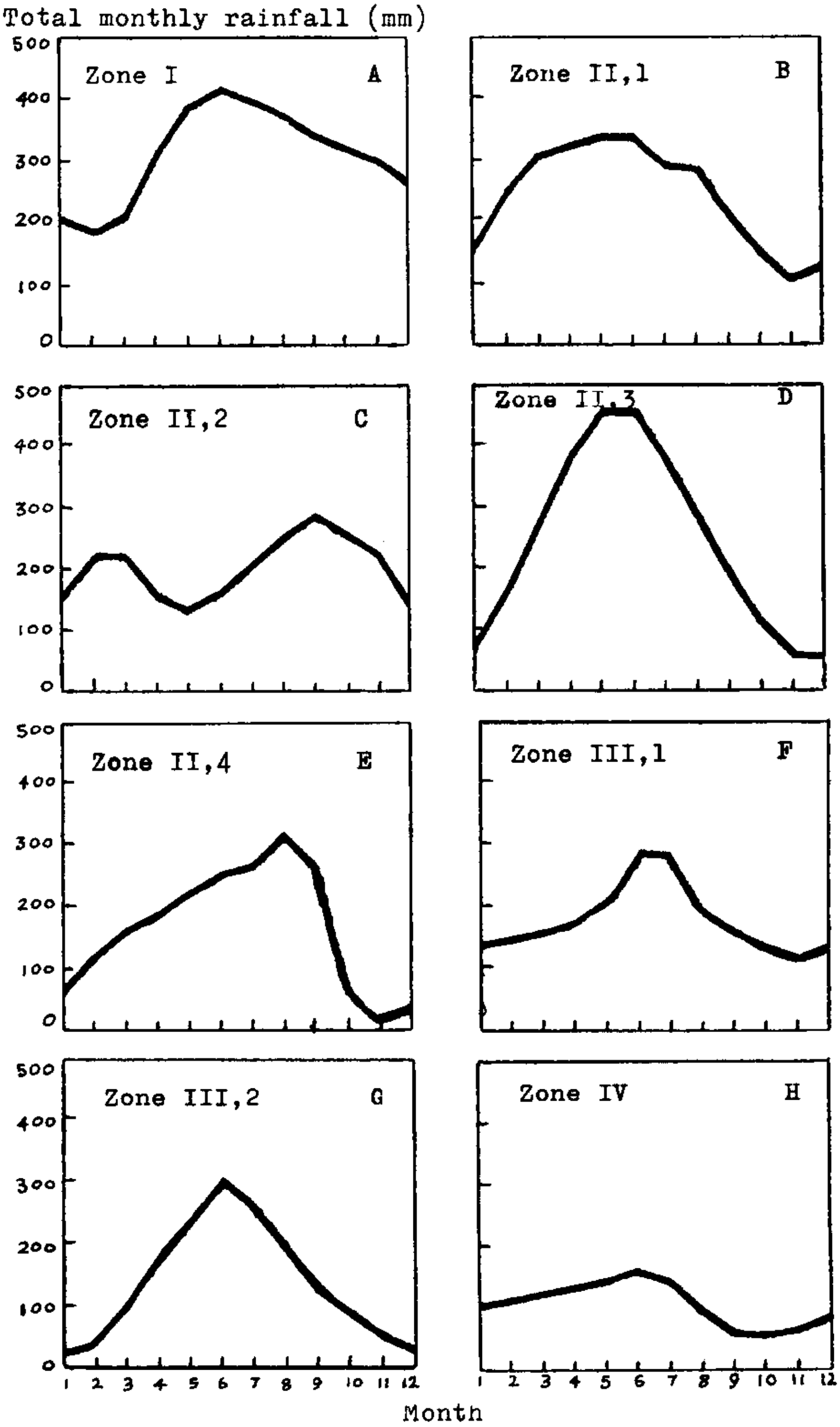

Figure 9—South-East Asian climatic zones as differentiated by rainfall pattern (Anonymous, 1974). See text for definitions of zones.

Zone II. Areas with five to nine consecutive wet months with more than 200 mm of rainfall. This zone covers the major part of Sumatra, the western and central part of Java, the major part of west Malaysia, the southern and eastern parts of Thailand, and the southern part of Burma. Eastern and central Luzon, Visayas and Mindanao in the Philippines come into this group. Major parts of Vietnam and Laos are also classified as Zone II.

Since this zone is of major interest for multiple-cropping, it is divided into four subdivisions:

Zone II_1. Areas with five to nine consecutive wet months and with 100 to 200 mm of rainfall per month during the remaining part of the year (*Figure 9B*). South Sumatra, south Borneo, west Java, north Sulawesi, north-east Malaysia, south-west Malaysia and Mindanao have this type of climate. They may be considered of particular interest for year-round cropping, with one crop of puddled rice.

Zone II_2. Areas with five to nine consecutive wet months and with 100 to 200 mm of rainfall per month during the remaining part of the year and with another minor rainfall peak (*Figure 9C*). These areas are found only north of the Equator but below latitude 10° N, e.g. north Sumatra, north Borneo, north-west Malaysia and the southern tip of the Thailand peninsula. This zone is equally suitable for multiple-cropping although farmers may grow two crops of puddled rice.

Zone II_3. Areas with five to nine consecutive wet months, including at least two months with less than 100 mm of rainfall (*Figure 9D*). This area covers large parts of central and east Java, southern Thailand, east and south-east Thailand, southern Burma and major parts of the Philippines.

Zone II_4 The areas in the south-east of Thailand are characterized by a sharp ending of the rainy season; the dry season in these areas and in Burma is very pronounced, with virtually no rain during two to three months (*Figure 9E*). The other extreme is found on the west coast of Burma where, during the rainy season, peaks of over 1 000 mm of rain per month occur. These areas may not be suitable unless some form of drainage exists, while the areas with an abrupt ending of the rainy season are also less ideal because very careful planning of planting dates is involved.

Zone III. Areas with two to five consecutive wet months. Although very often the wet season may be too short to grow two crops, a division has been made to separate areas that receive 100 mm or more of rainfall per month during the dry season and those that receive less than 100 mm per month during the dry season.

Zone III_1. Areas with two to five consecutive wet months but with at least 100 mm of rainfall per month during the remainder of the year (*Figure 9F*). These areas are located in major parts of Sulawesi, Malaysia, and northern Sumatra. They may have some prospect for multiple-cropping.

Zone III_2. Areas with two to five consecutive wet months and a pronounced dry season with at least two months less than 100 mm of rainfall per month (*Figure 9G*). East Java and the major part of central and north Thailand are covered by this pattern. The Island of Palawan in the Philippines, the central part of Vietnam and a large part of central Cambodia and southern part of Laos. Multiple-cropping is unlikely in these areas without additional water supply.

TABLE VII

Rainfall pattern for each zone (mm/month)

Zones	*Months*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Zone I	203	186	213	313	380	411	390	378	333	324	304	261
Zone II.1	158	249	306	328	339	341	287	286	213	152	105	135
Zone II.2	156	222	221	156	137	152	200	249	283	250	222	144
Zone II.3	80	162	277	384	453	453	372	289	187	107	58	52
Zone II.4	63	122	167	182	224	250	252	324	225	64	18	32
Zone III.1	136	147	156	176	212	289	282	193	158	135	115	128
Zone III.2	28	41	96	181	243	302	268	194	126	92	54	27
Zone IV	102	115	126	136	145	168	136	70	52	51	53	70

Climatic zones were drawn on a base map of South-East Asia (scale 1:8 million), included in this report (*Figures 9A, B*). It should be noted that these zones are rough estimates and contain many inclusions. (Anonymous, 1974).

Zone IV. Areas with less than two consecutive wet months. These areas are located in north-east Thailand, north Burma, east Kalimantan and some spots in Sulawesi, central Cambodia and central Visayas in the Philippines. They are not suitable for any type of agriculture unless additional water is available (*Figure 9H*).

Table VII shows the monthly precipitation values for the zones mentioned above. They are averages of available data and were used to draw *Figures 9A–H.* The months are numbered one to twelve because peaks of rainfall occur during different months in the northern and southern hemispheres.

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CHAPTER 7

BIOCLIMATIC CONDITIONS IN RICE-PRODUCING AREAS

7.1 **Survey data**

A questionnaire was sent by the author (as rapporteur) to a number of rice-research workers in many major and in some fringe rice-producing areas. Returns were received from 18 correspondents in countries ranging from almost 35° S through the equatorial zone to 44° N latitude (*Table VIII*). The type of information sought in the questionnaire is illustrated in *Tables VIII* to *XVI*, and was to be based on data which were representative of the rice-producing area involved in order that the data would reflect actual results from practical farm operations.

TABLE VIII

Rice-producing areas from which reports were received with locations arranged according to distance from Equator

Station		*Country*	*Latitude*	*Longitude*	*Elevation (m)*
No.	*Name*				
1	Kpong	Ghana	6° 08′ N	0° 04′ E	30
2	Kpong	Ghana	6° 08′ N	0° 04′ E	30
3	Nyankpala	Ghana	9° 24′ N	0° 58′ W	200
4	Pattambi	India	10° 48′ N	76° 12′ E	25
5	Pattambi	India	10° 48′ N	76° 12′ E	25
6	Los Baños	Philippines	14° 10′ N	121° 15′ E	21
7	Los Baños	Philippines	14° 10′ N	121° 15′ E	21
8	Tai Lung Farm	Hong Kong	20° 00′ N	114° 00′ E	38
9	Tai Lung Farm	Hong Kong	20° 00′ N	114° 00′ E	38
10	Tshaneni	Swaziland	26° 00′ S	31° 50′ E	305
11	Crowley	U.S.A.	30° 10′ N	92° 20′ W	8
12	Pelotas	Brazil	31° 52′ S	52° 21′ W	13
13	Concepción del Uruguay	Argentina	32° 29′ S	58° 21′ W	25
14	Chikugo-Shi	Japan	33° 30′ N	130° 30′ E	10
15	Stoneville	U.S.A.	33° 25′ N	90° 55′ W	39
16	Yanco	Australia	34° 22′ S	146° 25′ E	50
17	Stuttgart	U.S.A.	34° 28′ N	91° 25′ W	60
18	La Plata	Argentina	34° 55′ S	57° 57′ W	15
19	Takado	Japan	37° 06′ N	138° 15′ E	13
20	Ridgetown	Canada	42° 27′ N	81° 53′ W	206
21	Hokkaido Expt. Sta.	Japan	43° 00′ N	141° 25′ E	70
22	Asahikawa	Japan	43° 46′ N	142° 22′ E	112

Climatological averages were requested on a monthly basis. This information was plotted on graphs and averages or totals determined for various phenological stages. This technique facilitated the comparison of the bioclimatic conditions under which rice is grown in different areas and at different times of the year (e.g. *Table XI*).

Information on water temperature, irrigation amount, soil temperature and wind was also requested but reports were too incomplete to provide worth-while comparative information.

Some stations reported statistics on more than one crop where the wet season was sufficiently long or where irrigation was practised to permit more than one crop to be harvested per year.

The phenological data (*Table II*) are very approximate for a given area, since planting operations usually extend over a considerable period of time. It was suggested that an average sowing date be reported and that the dates of other phenological events be related to this average sowing date. Where rice was transplanted (T), the date of sowing was for nursery sowing. Otherwise the field-sowing date was reported.

TABLE IX

Rice-production statistics

Station		*Rice type*	*Cultural practice*	*Yield*			
No.	*Name*			*Grain (kg/ha)*	*Straw (kg/ha)*	*1 000-kernel weight (g)*	*Maximum height (cm)*
1	Kpong	Indica	Direct sowing	5 000	—	30	84
2	Kpong	Indica	Direct sowing	5 400	5 300	30	84
3	Nyankpala	Indica	Direct sowing[1]	4 500	—	—	115
4	Pattambi	Indica	Transplanted	2 272	5 240	27	121
5	Pattambi	Indica	Transplanted	2 000	2 400	26	101
6	Los Baños	Indica	Transplanted	4 500	6 500	19	115
7	Los Baños	Indica	Transplanted	6 500	6 500	20	100
8	Tai Lung Farm	Indica	Transplanted	2 500	3 000	22	110
9	Tai Lung Farm	Indica	Transplanted	2 700	3 500	19	85
10	Tshaneni	Indica	Direct sowing	3 176	—	33	86
11	Crowley	Indica	Transplanted	4 370	—	—	112
12	Pelotas	Japonica	Direct sowing	3 000	—	31	118
13	Concepción del Uruguay	Japonica	Direct sowing	6 000	—	32	100
14	Chikugo-Shi	Japonica	Transplanted	6 400	6 500	23	80
15	Stoneville	Indica	Direct sowing	5 044	—	23	114
16	Yanco	J60I40[2]	Direct sowing	7 400	7 500	28	105
17	Stuttgart	J × I[3]	Direct sowing	4 202	6 855	21	112
18	La Plata	Japonica	Direct sowing	8 000	—	30	85
19	Takado	Japonica	Transplanted	8 000	8 000	21[4]	95
20	Ridgetown	Japonica	Direct sowing	4 940	—	—	112
21	Hokkaido Expt. Sta.	Japonica	Transplanted	6 010	6 090	19[4]	78
22	Asahikawa	Japonica	Transplanted	4 100	—	22	80

[1] Upland. All others are flooded. [2] Japonica 60%, Indica 60%. [3] Japonica × Indica. [4] Hulled rice.

TABLE X

Rice agronomic data

Station		*Main variety*	*Average fertilizer per crop (kg/ha)*			*Major problems*
No.	*Name*		N	P_2O_5	K	
1	Kpong	SML Awini	53	56	—	Diseases, insects
2	Kpong	SML Awini	53	56	—	Diseases, insects
3	Nyankpala	*	145	218	18	Drought, blast
4	Pattambi	PTM	29	16	—	*
5	Pattambi	PTB-12, -20	29	16	—	*
6	Los Baños	IR 20	60	—	—	Typhoons, leaf hoppers
7	Los Baños	IR 20	60	—	—	
8	Tai Lung Farm	Fa Yui Tsai	45	34	17	Drought, Typhoons
9	Tai Lung Farm	Lio Shu Ngar	45	34	17	Insects, diseases
10	Tshaneni	Blue Bonnet 50	134	—	—	Insects, weeds
11	Crowley	Saturn	100	50	50	Hurricanes, heavy rain
12	Pelotas	EEA 404	*	*	*	Heavy rain, cold
13	Concepción del Uruguay	L.P. Itapé F.A.	Nil	Nil	Nil	*Pyricularia orizae*
14	Chikugo-Shi	Reiho	120	70	120	Disease, wind, flood
15	Stoneville	Starbonnet	336	—	—	Grass, weeds
16	Yanco	Calrose	50	—	—	Low temp., ducks
17	Stuttgart	Starbonnet	235	—	—	Stem rot, smut, blast
18	La Plata	L.P. Itapé F.A.	Nil	Nil	Nil	*
19	Takada	Koshihikari	60	60	60	Blast, stem borer
20	Ridgetown	Shinsetsu	91	121	121	Cool temp., birds
21	Hokkaido Expt. Sta.	Shiokari	*	*	*	*
22	Asahikawa	Shiokari	*	*	*	Cold air and water

* Data not supplied by station.

7.2 Climatic factors and variations in yield

Yields vary considerably from station to station, not only because of climatic conditions but also because of agronomic practices and varietal differences. For these reasons it is difficult to be specific as to the reasons for variations. Some generalization might be attempted, however, with caution.

The three areas with highest yields, Takado (8 000 kg/ha), La Plata (8 000 kg/ha) and Yanco (7 400 kg/ha) are at relatively high latitudes (*Tables VIII* and *IX*). Apart from the fact that a higher degree of agronomic technology may have been practised in the three areas with high yields, the climate of these three areas appears to be near the optimum for rice production. Average daily maximum temperatures are near or slightly below the optimum of 30°C during the main part of the growing period while average daily minimum temperatures are generally much above the minimum temperature of 15°C for good growth of *japonica* type of rice (*Tables XI* and *XII*). On the other hand, the yields at Tai Lung Farm, 2 500 and 2 700 kg/ha, and at Pattambi, 2 272 and 2 000 kg/ha (*Table VIII*), are the lowest of all stations reporting. The average daily maximum temperatures at both stations during the dry season are above the optimum for a good part of the growing season. During the wet season in the Pattambi area rainfall is so high that excessive water may frequently lower the yield. Lack of adequate rain and insufficient irrigation water may also reduce yield during the dry season in both the Pattambi and Tai Lung Farm areas (*Table XIII*). From the scanty information on solar radiation and bright sunshine it appears that, in the Pattambi area during both seasons, the available radiation will be exceptionally low, while in the Yanco area available radiation is high, based either on average daily global radiation (*Table XIV*) or on the percentage of bright sunshine (*Table XV*).

TABLE XI

Average daily maximum temperatures at various phenological stages (°C)

Station		S – 30[1]	S	E	T	MT	PPI	H	DS	M	M + 30[2]
No.	*Name*										
1	Kpong	35.6	35.0	34.9	(33.8)	33.5	33.4	33.3	32.3	31.2	30.3
2	Kpong	30.0	31.2	31.3	(32.5)	32.9	32.9	32.8	33.0	33.5	35.7
3	Nyankpala	33.7	32.2	32.0	(30.1)	29.0	28.3	30.3	32.7	35.2	35.7
4	Pattambi	34.0	30.9	30.4	29.6	29.4	29.4	28.8	29.8	31.0	32.3
5	Pattambi	29.0	29.9	30.1	32.0	32.0	31.8	32.2	33.7	34.0	35.0
6	Los Baños	32.8	32.3	32.2	31.4	31.1	30.7	30.4	30.0	30.0	29.9
7	Los Baños	30.0	28.9	28.9	28.9	28.8	29.0	29.6	30.5	31.8	32.8
8	Tai Lung Farm	19.2	23.0	23.8	27.4	30.4	32.0	32.4	34.0	34.0	33.0
9	Tai Lung Farm	31.5	33.6	33.9	33.7	32.8	32.0	31.8	29.3	27.5	27.4
10	Tshaneni	27.8	28.0	27.3	(29.7)	30.5	31.1	31.3	30.5	29.6	28.8
11	Crowley	19.3	23.2	24.1	(28.2)	27.7	31.1	32.2	32.3	32.5	32.1
12	Pelotas	21.6	24.0	24.5	(27.6)	29.3	29.4	28.4	28.0	27.1	24.3
13	Concepción del Uruguay	21.0	24.6	26.7	(29.3)	28.2	31.0	30.6	28.9	23.4	21.9
14	Chikugo-Shi	21.5	25.7	26.2	28.4	32.1	32.2	30.0	26.3	20.8	15.5
15	Stoneville	21.7	26.5	27.5	(31.3)	33.5	33.5	33.0	31.0	29.0	22.8
16	Yanco	16.6	20.2	23.3	(27.9)	29.1	30.4	30.8	27.8	24.1	18.4
17	Stuttgart	18.9	25.1	26.6	(31.0)	32.5	32.3	31.7	30.3	27.7	23.8
18	La Plata	16.8	19.3	22.0	(25.5)	28.8	28.8	28.0	26.3	25.0	20.0
19	Takada	9.0	16.2	17.2	23.0	28.9	30.7	30.9	28.5	23.3	17.8
20	Ridgetown	14.6	20.3	23.3	(25.9)	26.0	26.0	25.3	24.0	22.2	15.7
21	Hokkaido Expt. Sta.	9.3	14.3	15.0	18.0	24.9	23.2	25.3	23.1	19.1	13.8
22	Asahikawa	3.2	11.8	13.2	19.9	26.2	25.8	27.0	25.1	19.1	12.0
Average		22.6	25.2	26.2	28.4	29.9	30.2	30.3	29.5	27.7	25.4

[1] 30 days before sowing.
[2] 30 days after maturity.
( ) indicates value (temperature) 30 days after emergence for direct-sowing of crops in field.
See *Table II* for explanation of other phenological stages.

TABLE XII

Average daily minimum temperatures at various phenological stages (°C)

Station *No.*	*Name*	S – 30	S	E	T	MT	PPI	H	DS	M	M + 30
1	Kpong	22.8	23.3	23.3	(23.2)	22.9	22.8	22.9	22.8	22.3	21.7
2	Kpong	21.7	21.8	21.8	(21.8)	21.9	21.9	21.9	21.6	21.2	22.8
3	Nyankpala	23.7	22.7	22.7	(22.7)	21.9	21.8	21.8	21.9	21.9	20.0
4	Pattambi	23.8	23.0	23.0	22.5	22.4	22.4	21.6	21.7	22.7	21.8
5	Pattambi	22.0	22.1	22.2	22.2	21.1	21.0	20.1	20.0	19.9	20.3
6	Los Baños	25.0	24.5	24.7	25.6	25.1	24.5	24.5	24.6	24.8	25.0
7	Los Baños	25.0	23.9	23.8	22.9	22.5	22.5	22.9	24.5	24.7	25.0
8	Tai Lung Farm	9.0	12.2	13.0	16.6	21.5	22.9	23.4	25.5	25.7	23.2
9	Tai Lung Farm	22.3	24.9	25.1	24.8	22.9	22.4	21.9	19.2	17.5	13.0
10	Malkerns	14.5	16.1	16.3	(18.1)	19.6	21.0	21.7	21.3	20.6	18.8
11	Crowley	8.6	12.2	13.4	(17.13)	17.0	20.6	22.7	22.8	23.0	21.7
12	Pelotas	11.9	13.3	13.7	(15.8)	17.4	17.8	17.2	16.9	16.0	12.0
13	Concepción del Uruguay	9.5	12.4	13.4	(15.2)	14.3	16.8	16.7	15.7	12.8	8.9
14	Chikugo-Shi	12.2	15.0	15.6	19.8	23.9	23.2	20.8	16.4	10.0	5.0
15	Stoneville	8.7	13.3	14.6	(18.9)	21.3	21.3	21.8	18.6	15.3	8.8
16	Yanco	4.7	7.7	9.7	(12.5)	14.9	15.9	17.6	14.3	11.1	7.8
17	Stuttgart	8.0	13.8	15.0	(19.2)	21.3	21.3	20.3	18.6	17.6	10.5
18	La Plata	7.3	9.2	11.0	(14.0)	16.8	16.8	16.7	15.6	14.9	10.0
19	Takada	–0.2	4.7	5.9	13.2	20.8	21.9	21.8	19.2	14.0	7.8
20	Ridgetown	4.2	9.5	13.1	(16.4)	16.6	16.6	15.8	14.4	12.7	7.5
21	Hokkaido Expt. Sta.	0.0	4.0	4.6	7.8	17.4	15.4	17.7	14.1	8.7	2.0
22	Asahikawa	–6.4	0.6	1.6	7.1	15.8	15.0	17.4	15.0	8.3	1.8
	Average	12.7	15.0	15.8	18.1	20.0	20.3	20.4	20.2	17.5	14.3

See *Tables II* and *XI* for explanation of phenological stages and use of ( ).

TABLE XIII

Accumulated rain (mm) from 30 days prior to sowing

Station *No.*	*Name*	S – 30	S	E	TP	MT	PPI	H	DS	M	M + 30
1	Kpong	0	65	85	(205)	330	415	517	623	690	770
2	Kpong	0	80	100	(238)	340	397	405	414	440	477
3	Nyankpala	0	40	50	(92)	145	200	235	255	270	300
4	Pattambi	0	275	360	920	1 665	1 720	2 035	2 190	2 300	2 466
5	Pattambi	0	198	220	450	540	555	595	596	597	598
6	Los Baños	0	195	215	350	695	915	1 015	1 145	1 260	1 560
7	Los Baños	0	260	280	375	425	430	450	465	475	557
8	Tai Lung Farm	0	40	60	110	210	400	495	750	815	1 219
9	Tai Lung Farm	0	360	390	640	1 000	1 110	1 130	1 185	1 220	1 240
10	Tshaneni	0	15	45	(125)	175	245	355	410	490	575
11	Crowley	0	229	280	(480)	460	630	895	1 045	1 215	1 520
12	Pelotas	0	110	125	(193)	272	320	450	525	578	—
13	Concepción del Uruguay	0	159	210	(330)	260	497	525	587	720	850
14	Chikugo-Shi	0	195	223	500	880	997	1 167	1 340	1 422	1 500
15	Stoneville	0	128	155	(270)	355	355	480	520	555	635
16	Yanco	0	40	65	(110)	135	150	180	225	245	281
17	Stuttgart	0	84	120	(220)	285	320	440	500	530	605
18	La Plata	0	95	190	(295)	420	420	490	605	670	771
19	Takada	0	160	190	320	545	640	715	835	1 065	1 250
20	Ridgetown	0	85	140	(230)	250	235	305	350	380	441
21	Hokkaido Expt. Sta.	0	60	70	135	300	270	335	420	590	690
22	Asahikawa	0	60	65	140	290	270	380	480	625	733
	Average	0	133	165	306	454	522	618	703	835	907

See *Tables II* and *XI* for explanation of phenological stages and use of ( ).

TABLE XIV

Average daily global solar radiation at various phenological stages (cal cm^{-2} day^{-1})

Station		S − 30	S	E	T	MT	PPI	H	DS	M	M + 30
No.	*Name*										
1	Kpong										
2	Kpong										
3	Nyankpala										
4	Pattambi										
5	Pattambi										
6	Los Baños	490	427	422	395	369	368	361	354	336	304
7	Los Baños	313	289	290	317	416	441	465	504	546	490
8	Tai Lung Farm										
9	Tai Lung Farm										
10	Tshaneni										
11	Crowley										
12	Pelotas	360	466	483	(517)	518	506	428	400	364	295
13	Concepción del Uruguay										
14	Chikugo-Shi	410	395	384	388	422	385	351	315	248	187
15	Stoneville	452	539	561	576	556	556	502	450	412	336
16	Yanco	418	525	613	(716)	708	703	678	520	419	300
17	Stuttgart										
18	La Plata										
19	Takada										
20	Ridgetown										
21	Hokkaido Expt. Sta.	350	391	393	410	408	418	387	342	270	188
22	Asahikawa	292	349	354	380	376	378	342	310	250	190
Average		386	423	438	462	472	469	439	399	356	286

See *Tables II* and *XI* for explanation of phenological stages and use of ( ).

TABLE XV

Average daily percentage of bright sunshine at various phenological stages

Station		S − 30	S	E	T	MT	PPI	H	DS	M	M + 30
No.	*Name*										
1	Kpong										
2	Kpong										
3	Nyankpala										
4	Pattambi	32	20	19	12	17	19	24	26	27	34
5	Pattambi	24	26	26	31	34	34	37	40	40	41
6	Los Baños										
7	Los Baños										
8	Tai Lung Farm										
9	Tai Lung Farm										
10	Tshaneni										
11	Crowley										
12	Pelotas	50	58	60	(63)	59	58	56	60	61	52
13	Concepción del Uruguay	64	67	74	(63)	69	70	71	67	64	62
14	Chikugo-Shi	42	39	38	36	37	53	46	47	52	44
15	Stoneville	57	63	65	(69)	69	69	74	73	73	69
16	Yanco	67	69	69	(70)	68	72	73	71	70	65
17	Stuttgart										
18	La Plata										
19	Takada	39	49	50	45	41	48	54	45	40	40
20	Ridgetown										
21	Hokkaido Expt. Sta.	—	51	49	44	43	43	43	47	52	—
22	Asahikawa	44	46	46	45	39	40	40	41	41	36
Average		46	49	50	48	48	51	52	52	52	49

See *Tables II* and *XI* for explanation of phenological stages and use of ( ).

TABLE XVI

Evaporation from Class A pan evaporimeter at various phenological stages (mm/day)

Station No.	*Station* Name	S−30	S	E	T	MT	PPI	H	DS	M	M + 30
1	Kpong[1]	6.6	7.1	7.1	(6.1)	6.1	5.8	4.9	4.7	4.6	4.6
2	Kpong[1]	6.6	4.8	4.9	(5.1)	4.8	4.7	4.6	4.7	5.1	6.6
3	Nyankpala										
4	Pattambi	4.7	3.0	2.8	1.4	1.4	1.6	2.2	2.7	3.1	3.7
5	Pattambi	2.1	2.7	2.8	3.5	3.9	4.0	5.4	6.4	4.5	6.8
6	Los Baños	5.6	5.3	5.3	5.2	4.5	4.4	4.2	3.7	3.6	3.4
7	Los Baños	3.5	3.2	3.2	3.6	4.5	4.7	5.0	5.3	5.5	5.6
8	Tai Lung Farm										
9	Tai Lung Farm										
10	Tshaneni	6.3	6.5	5.8	(7.0)	7.6	7.6	6.6	6.5	6.4	5.7
11	Crowley	2.8	3.6	3.8	(4.6)	4.6	5.1	4.9	4.7	4.7	4.1
12	Pelotas[2]	2.9	4.0	4.2	(4.9)	4.9	4.7	4.1	3.5	3.0	1.8
13	Concepción del Uruguay										
14	Chikugo-Shi										
15	Stoneville	4.2	5.7	6.0	(7.1)	6.9	6.9	5.9	5.1	4.5	3.4
16	Yanco	2.5	3.8	5.0	(6.8)	7.4	7.5	7.4	5.3	4.1	2.4
17	Stuttgart	4.1	5.6	6.0	(7.2)	7.1	6.9	5.9	5.3	4.8	3.6
18	La Plata										
19	Takada										
20	Ridgetown	—	5.1	5.9	(6.5)	6.5	6.5	5.9	5.0	3.9	2.3
21	Hokkaido Expt. Sta.										
22	Asahikawa										
Average		4.3	4.6	4.8	5.7	5.4	5.4	5.2	4.8	4.4	4.2

[1] Type of evaporimeter not specified.

[2] Values calculated by means of Penman formula.

See *Tables II* and *XI* for explanation of phenological stages and use of ( ).

7.3 Climatic limits to regional yield

The production of rice is limited by the following climatic elements:

(*a*) Low temperature limiting the duration of the growing season;
(*b*) Low temperature during the growing season limiting the rate of growth and development;
(*c*) High temperature during the growing season causing a deleterious thermal stress;
(*d*) Insufficient water;
(*e*) Excessive flooding;
(*f*) Low global solar radiation limiting the rate and amount of photosynthesis;
(*g*) Long photoperiod limiting the choice of suitable varieties.

One or more of these limitations appear to be at work in several of the areas for which the survey was made. Again it must be pointed out that the limiting climatic element was not positively determined analytically but was only identified subjectively. Elements (*a*)–(*f*) are considered in turn below.

Temperature limitations to the duration of the growing season are evident at Takada, Hokkaido Exp. Sta. and Asahikawa (*Table XII*). In these areas the average daily minimum temperatures are below 5 °C at either the beginning or end of the growing period and imply a high risk of freezing temperatures. Under such conditions it is necessary to take special precautions in the spring to protect nursery seedlings from low temperatures and rapidly developing varieties must be used which will mature early in the autumn.

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Low temperatures during the early and late parts of the growing season appear to be limiting in most areas at latitudes greater than 30° (*Tables XI* and *XII*). These low temperatures not only limit photosynthesis and general growth but they also slow down the rate of development which in turn aggravates the situation because of the limited duration of the available growing season.

Deleteriously high temperatures appear to occur in areas at low latitudes during the drier seasons. Kpong, Pattambi, Tai Lung Farm, and Stoneville have the highest average daily minimum temperatures which may be accompanied by a high risk of temperatures in excess of the optimum for rice growth (*Table XI*).

Low average rainfall is characteristic of areas around Nyankpala, Tshaneni, Yanco and Ridgetown and also around Kpong, Pattambi and Los Baños during their dry seasons. There is a high risk of drought in these areas and controlled irrigation is necessary for good crop yields. Where irrigation depends on rainfall and streamflow, crop failures are not uncommon. To aggravate the situation, potential evapotranspiration is generally high where rainfall is low. Such is the case at Tshaneni and Yanco (*Table XVI*).

Heavy rainfall and excessive flooding are indicated in the areas around Pattambi, Los Baños, Crowley and Chikugo-Shi where growing- or wet-season rainfall exceeds 1 500 mm (*Table XIII*). Other areas with lesser rainfall, such as those in the vicinity of Tai Lung Farm and Pelotas, may suffer from floods in some years (*Table IX*). In some areas flooding can be controlled by dikes and drainage systems, but this is not always possible because of topographical and technical problems.

Low global solar radiation (in spite of the common misconception that tropical areas have an abundance of sunshine) is frequently limiting, particularly in areas of heavy rain and cloudy skies such as Pattambi, Los Baños, Chikugo-Shi, Hokkaido and Asahikawa. Research at IRRI (De Datta and Zarate, 1970) indicates that high solar radiation 30 to 45 days prior to harvesting contributes to high yields. This is well illustrated by the yield (*Table VIII*) for Los Baños which was 6 500 kg/ha when water was supplied by irrigation and radiation was high. On the other hand the yield was only 4 500 kg/ha during the wet season when radiation was low (*Table XIV*). In general, global solar radiation, as reported at some stations, was highest at or prior to the time of maximum tillering and decreased from then until maturity, a condition which is not the most favourable for highest yields.

7.4 **Conclusions**

From the foregoing brief discussion of regional conditions it is obvious that many bioclimatic elements affecting rice make a very complex and contradictory contribution to the growth and final yield of the crop. In order to appraise the real contribution of each of these elements a comprehensive analytical procedure is necessary such as has been used for corn by Amores-Vergara (1973), for wheat by Baier (1973) and Robertson (1968, 1974*b*), and for barley by Williams (1974). Although such techniques might make use of existing historical-yield and weather data (Robertson, 1974b), it might be advantageous to set up an international experiment to gather special data for such an analysis as proposed by Robertson (1973).

Acknowledgements

Many people, too numerous to mention, contributed in many ways to my meagre knowledge of the effects of weather on rice production while I was on an UNDP/WMO Technical assignment in the Philippines in 1969–71 and again when I visited several countries in South-East Asia in 1972 as a consultant to the WMO/FAO/Unesco/UNDP Interagency Group on Agricultural Biometeorology.

In particular I wish to acknowledge the assistance of my wife, Lucille, who typed the first draft of this report. Also I wish to acknowledge the valuable contributions of those people who answered the questionnaire concerning rice and climate and many of whom sent me technical bulletins and reprints of scientific papers.

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Printed in Great Britain by William Clowes & Sons Ltd., London, Colchester and Beccles

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