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Characterizing Asian wind-dust transport to the Northwest Pacific Ocean. Direct measurements of the dust flux for two years

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ABSTRACT

Based on an observation at the North Yellow Sea (Huanghai) over 2 years, this study describes main features (pH, EF Ca and flux etc.) associated with the wind-dust transport from East Asia (China) to the Northwest Pacific Ocean. Compositions of the atmospheric deposition are highly variable over the China Sea, with elevated dust flux ($\sim 40\ g\ m^{-2}\ yr^{-1}$) and poor rainfall in winter and spring in comparison to abundant rainfall and low dust flux ($\sim 10\ g\ m^{-2}\ yr^{-1}$) in summer and autumn. However, atmospheric dust fallout from winter and in spring differs in pH and EF Ca values. Examination of data refines that the wind-dust from Siberia/Mongolia and Northwest China has significant impact upon the chemical composition and flux of atmospheric fallout over the China Sea, although anthropogenic influences on the rain/snow chemistry have been identified. Annual wind-dust flux to the China Sea is estimated at $53.7\ g\ m^{-2}\ yr^{-1}$, which is one order of magnitude higher than that over the Central North Pacific Ocean.

1. Background

Extensive studies of atmospheric fallout have been made over North Pacific Ocean since 1970s (cf. GESAMP, 1989 and references within). The main conclusion is probably that the mineral particles are transported from arid regions in the North Asia to the North Pacific Ocean over 5,000–10,000 km and the annual dust deposition appears to be dominated by sporadic dust events of short duration (cf. Tsunogai and Kondo, 1982; Blank et al., 1985; Uematsu et al., 1985; GESAMP, 1989). Mineral aerosol is important to the sedimentation of the North Pacific Ocean due to its wide distribution from 10°N to 60°N and high flux of $50–450\ mg\ m^{-2}\ yr^{-1}$ (Duce et al., 1980; Uematsu et al., 1983). Ferguson et al. (1970) found the similarity of clay mineral assemblages in atmospheric dust over the North Pacific to those of the deep-sea sediments from the same area, and sedimentary studies revealed that 70–90% of the surface sediment in Central North Pacific is derived from atmospheric dust fallout (Janecek, 1985; Schramm and Leinen, 1987). The deposition rate of mineral aerosols ($10–20 \times 10^{12}\ g\ yr^{-1}$) in the Central North Pacific Ocean is comparable to the sediment load of some large Asian rivers draining into the Northwest Pacific Ocean.

There are, however, very few direct measurements of Asian dust deposition to the Northwest Pacific, which have extended over a sufficiently long time to permit determination of the seasonal and interannual variabilities of dust transport. How seaward transport of wind dust might be related to meteorological/climatological conditions and geographic positions remains unclear.

2. Sample collection and methods

To select proper a site for atmospheric monitoring stations, we considered that (a) the sampler should be set as far as possible from urban areas to

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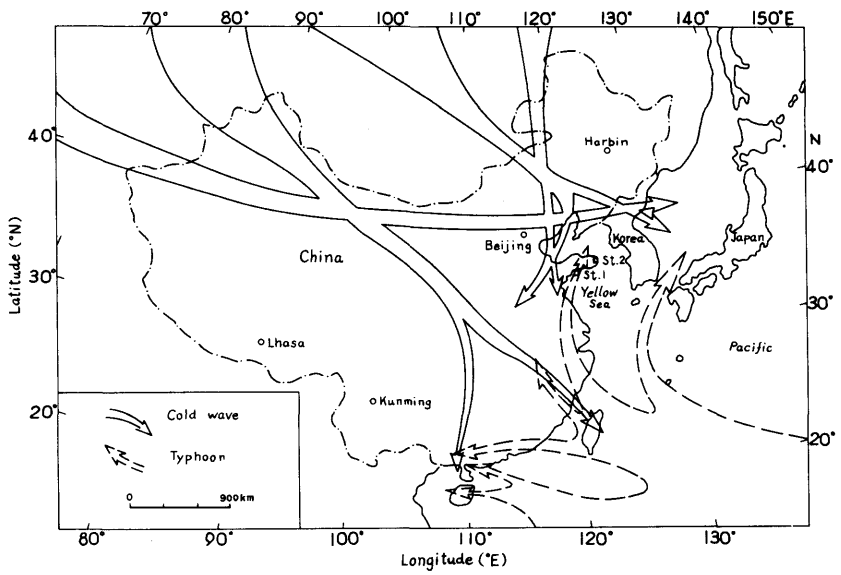

Fig. 1. Map of China. It shows trajectories of cold wave and typhoon. The atmospheric monitoring stations (St. 1 and St. 2) are located to the Northwest of the Huanghai (Yellow Sea).

eliminate local pollution influences, and (b) the sample stations should be on the small islands or close to the coast line to receive marine air mass and decrease the turbulence of air circulation due to local geography (e.g., relief). In this study, we chose the station close to 40°N of latitude, since from the previous studies, mid-latitude is the major pathway for Asian wind-dust to the Northwest Pacific Ocean. Observations were undertaken at the meteorological stations to the northwest of Huanghai (Yellow Sea) at 95 m (St. 1) and 50 m (St. 2) above sea level respectively, but we report here the data of the St. 1 (Fig. 1). Data from St. 2 will be discussed elsewhere. The distance of the St. 1 to the coast line is ca. 600 m. Systematic observations on atmospheric fallout have been made since October 1988. Two clean conic plastic gauges of 400 cm^2 in surface and 40 cm in height were used: one is open only when rain and/or snow drops to collect wet deposition (A), another is open all the time to collect bulk deposition (wet + dry) (B). The samplers are installed at the seaward side on the top of a hill to minimize influences from local pollution. The gauge is covered with a pre-cleaned porous plastic funnel to eliminate large debris (e.g., tree leaves). In order to eliminate resuspension of dry fallout which may take place, especially with snow events and bias the flux estimate of dry deposition, the funnels were taken off in winter. Furthermore,

Table 1. *Chemical compositions (μM) of natural and artificial rainwaters used in leaching experiments*

Rain	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	NO_3^-	NH_4^+	Cl^-	pH
natural	15.0	4.1	4.3	7.7	54.1	1.8	18.3	11.5	4.64
artificial	39.9	14.4	143.5	11.3	129.0	114.5	116.1	219.4	3.99

The natural rain sample was collected on the top of a building (close to St. 1) between 30 May and 1 June 1991. The sample was filtered and than kept frozen until use. Artificial rain sample was prepared by dissolving $MgSO_4$, $NaNO_3$, K_2SO_4, $CaCl_2$, $(NH_4)_2SO_4$ and NaCl in double distilled water. The pH of the artificial rainwater was then adjusted to ~4.0 with dilute HCl. All the salts are of GR grade.

we note that the collection of only and perfect rain/snow is difficult and the defect of manipulation (e.g., failure in opening gauge cover in time) would affect the wet deposition estimate, which may result in an under-estimate of rainfall by 10%. When the rainfall was less than 1 mm, samples were filtered to get the particle flux of wet and total depositions, but pH and chemical analyses were not undertaken. The sampling period ranged from several hours to one mouth, depending upon the duration and frequency of precipitations.

Rain and melt snow waters plus particles were filtered with 0.45 μm Sartorius filters to estimate dust depositions. Differences between samples B and A were taken as from the contribution of dry fallout. In order to testify the wind-dust regulation of rain pH, we carried out two experiments in the laboratory: soil dusts over the Quaternary Loess Plateau in North China (loess is the major source of dust storm in North China) were collected and leached with natural and artificial rain waters. The artificial rain-water was prepared following average chemical composition of rain samples in this study (Table 1). In the experiments, dust content was controlled at 50 mg l^{-1}, and the solutions (200 ml each) were agitated in a closed system to prevent from exchange with ambient air. The pH was measured with potentiometry. Dissolved Na^+ and Ca^{+2} were determined with atomic absorption spectrometry. Duplicate samples were analysed and the differences between two determinations were $<5\%$. Ammonium of laboratory experiment samples was determined with spectrophotometry.

3. Results and discussion

The annual rainfall is highly variable in this study: it ranged from ~480 mm in 1989 to ~550 mm in 1990. Long term observations indicate that the rainfall over the study area ranged from 250 mm to 1250 mm between 1900 and 1985 with 710 mm in average. The observation data of this study are summarized in Table 2, including rainfall (mm), pH value, and concentrations of Na and Ca in wet deposition. This study was aimed to describe the magnitude of wind-dust transport/deposition over the China Sea (marginal zone of the Northwest Pacific Ocean), and the influence of mineral dust from Siberia/Mongolia and northwest of China upon element concentration and acidity of atmospheric precipitation. Emphasis is given to the variabilities and deposi-

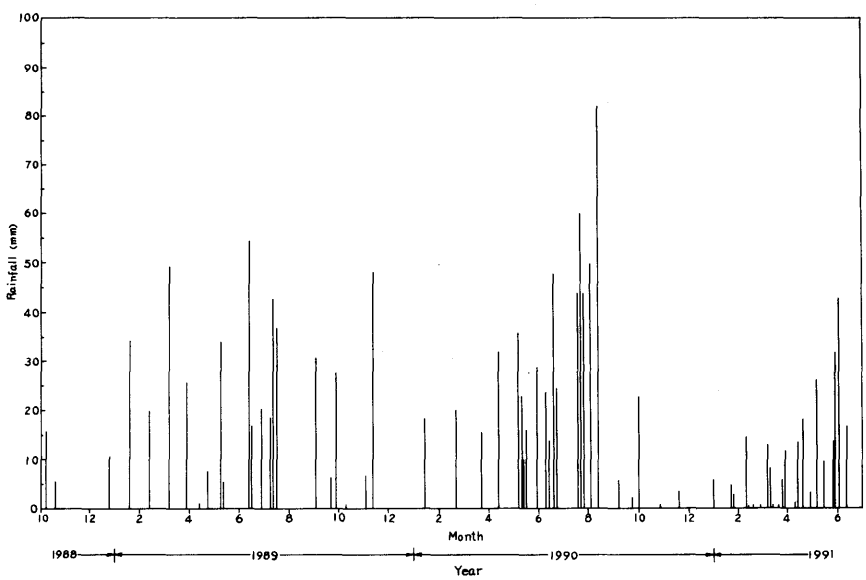

Fig. 2. Rainfall (mm). Individual rain events during this study are shown. Note that rainfall between May and August is quite abundant, it may account for 60–80% of whole year's atmospheric precipitation.

tions of Asian wind-dust and the correlation of high wind-dust flux to the China Sea with sporadic dust storm events over the North China, since the Asian wind-dust has important impact upon the geochemistry and sedimentology in the North Pacific Ocean.

3.1. *Field observations*

Fig. 2 summarizes successive rain fall events from October 1988 to June 1991. Abundant rainfall appears between May and August, accounting for 60–80 % of the whole-year deposition.

High dust concentrations in rain water (which may reach 100–500 mg l^{-1}) also occurs in spring (Fig. 3a). It is evident from Fig. 3 that rain particle content in summer ranges from 0.5 to 20 mg l^{-1} when the atmospheric precipitation is quite abundant, whereas elevated dust values ($>$50–100 mg l^{-1}) appear between November and June when north wind monsoons prevail over the China. Concentrations of Ca and Na in the wet deposition (rain + snow) ranges from 5–10 μM to 500–1000 μM in this study (Table 2). Elevated Ca and Na values (e.g., $>500\,\mu$M) have been observed in winter and spring when the rainfall was small ($<$5–10 mm). The pH values of rain and melt snow water (wet deposition) are generally <5.65 from summer to winter and increase to 6–7 in spring (Fig. 3b). Data in Table 2 show that pH values of rain and snow may fall to <4.0 in winter most likely due to the atmospheric pollution (e.g., emission of SO_2 and NO_x related to combustion of fossil fuels) (Huang and Zhao, 1987). The extreme acid deposition events (pH <4.0) may occasionally occur in spring, but the reason is still not known. The calcium enrichment factor (EF Ca), which is often considered from non-marine source contributions, is defined as:

$$\text{EF Ca} = (\text{Ca/Na})_R/(\text{Ca/Na})_S - 1$$

$$= [(\text{Ca}_R/\text{Ca}_S) \times (\text{Na}_S/\text{Na}_R) - 1] \qquad (1)$$

where R = rain water, S = sea water.

The enrichment factor (EF Ca) may serve as an index of non-marine calcium sources (e.g., calcium coming from soil dusts) in eq. (1). However $(\text{Ca/Na})_R$ in the equation may involve contributions of Na from dust dissolutions (e.g., soil salts) and may give an under-estimate of non salt Ca. Values of EF Ca range from 5 to 245 unit in this study (Fig. 3c). High EF Ca values ($>$100–150)

Table 2. *Concentrations (μM) of Na, Ca and pH values of the wet depositions to the Northwest Huanghai (Yellow Sea) during the observations from 1988 to 1991*

Year	Date MM-DD	Rainfall (mm)	Ca (μM)	Na (μM)	EF Ca	pH
1988	11.16	21.1	124.8	234.9	23.1	4.26
	12.24	10.1	147.2	365.4	17.2	4.48
1989	1.18	34.3	59.9	121.8	21.3	4.20
	3.05	49.8	29.9	52.2	24.9	4.07
	3.27	25.6	10.0	13.0	34.0	4.73
	5.08	39.1	129.7	34.8	168.5	6.68
	6.12	54.8	67.4	47.8	63.1	5.28
	6.13	17.3	10.0	8.7	51.3	4.72
	6.27	20.1	25.2	27.8	40.4	5.93
	7.07	18.5	25.9	90.9	11.7	4.15
	7.10	43.0	4.7	8.7	23.5	4.20
	7.14	32.0	9.5	84.4	4.0	4.35
	9.02	31.0	159.9	110.0	64.9	3.67
	9.26	27.6	18.5	32.6	24.9	4.55
	11.03	6.8	190.4	281.0	29.9	4.14
	11.12	48.5	18.5	27.0	30.4	4.46
1990	1.14	18.5	29.2	25.7	50.8	3.69
	2.17	11.0	21.0	157.5	4.9	4.05
	3.22	15.8	57.4	31.3	82.2	4.39
	4.12	32.0	59.6	43.9	60.8	4.26
	5.06	36.0	69.1	13.0	240.8	6.63
	5.09	23.0	53.6	42.6	56.3	4.81
	5.13	30.0	23.7	45.7	22.6	4.23
	5.30	28.7	25.0	28.3	39.0	5.17
	6.09	4.0	62.4	28.3	99.0	4.85
	6.13	12.0	124.8	54.4	103.1	5.75
	6.19	45.0	8.0	19.6	17.6	4.36
	6.20	19.5	5.0	3.3	69.0	4.60
	7.15	24.0	6.2	17.4	15.4	4.50
	7.24	44.0	10.0	15.2	29.0	4.77
	8.03	50.0	10.0	26.1	16.3	4.21
	8.13	82.0	62.4	100.0	27.2	6.07
	8.31	23.0	16.2	30.4	23.1	4.47
	9.07	12.0	12.5	10.9	51.3	4.46
	11.18	3.5	1422.2	435.0	147.6	5.38
1991	1.02	6.0	923.1	478.5	86.7	5.69
	1.20	5.0	361.8	137.0	119.0	4.87
	1.23	3.0	142.2	169.6	37.2	4.20
	2.10	15.0	31.2	17.4	80.4	3.91
	3.07	13.0	88.6	34.8	114.9	3.92
	3.10	8.5	52.4	30.4	77.2	3.91
	3.24	6.0	117.3	39.1	135.4	4.01
	4.10	1.5	108.5	34.8	140.8	6.06
	4.12	12.5	22.5	10.9	92.6	3.89
	4.17	18.5	31.2	17.4	80.4	4.78
	4.28	3.5	524.0	130.5	181.7	6.40
	5.05	26.5	71.1	17.4	184.9	5.40
	5.14	10.0	274.5	58.7	211.7	6.71
	5.24	14.0	21.2	8.7	109.9	4.22
	5.25	32.0	37.4	17.4	96.7	4.24
	6.01	43.0	13.1	4.3	137.6	4.16
	6.10	18.0	43.7	26.1	74.9	5.97

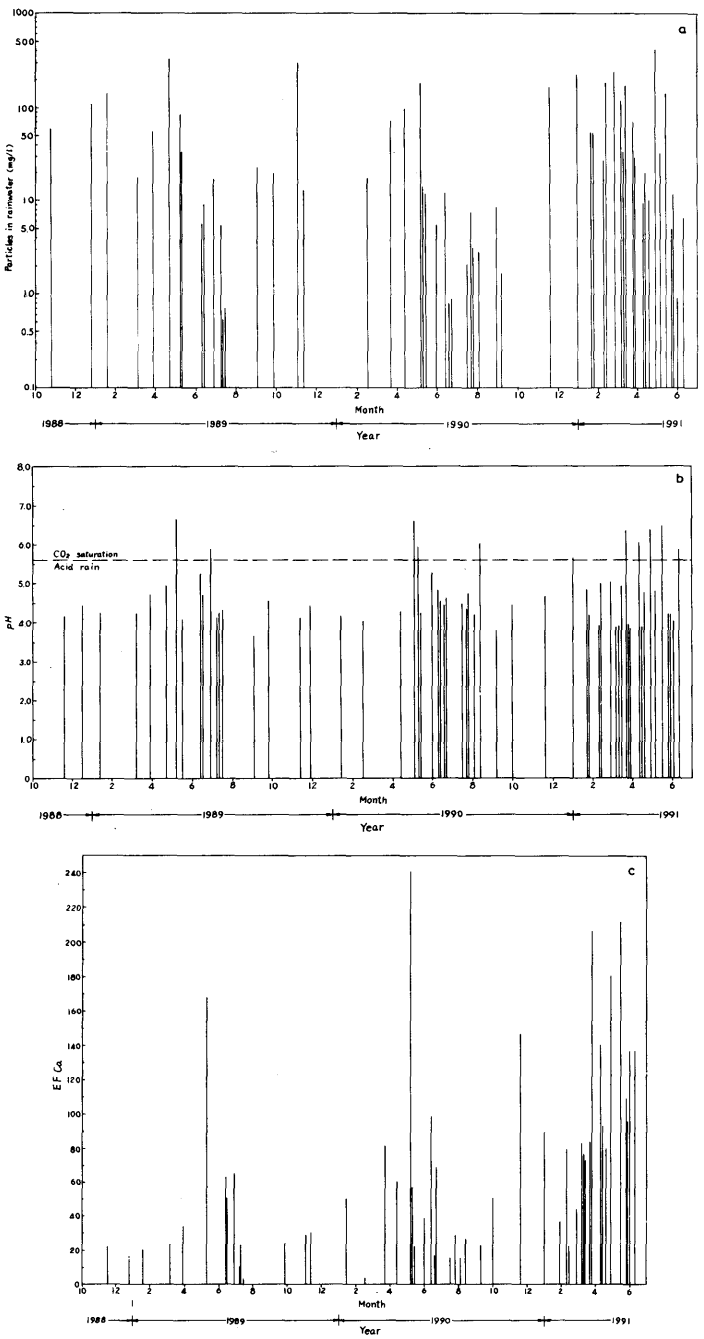

Fig. 3. Content of particles (mg l^{-1}), pH and EF Ca in rain water. Note that high particle concentrations in rain water occur in winter and spring, which may be one order of magnitude higher than those in summer and autumn. Generally pH values of rain water are lower than 5.65; high pH values (>5.65) have been observed in spring corresponding to elevated particle concentrations and EF Ca values in rainwater. (a) Content of particles; (b) pH values; (c) EF Ca values.

occur exclusively in Spring (with one exception), when north wind monsoons predominate over China and East Asia; whereas during summer, whenever southeast and southwest monsoons prevail, EF Ca values of rainwater are generally less than 30–50 unit (Figs. 2, 3). Inspection of the data in Fig. 3 reveals the coincidence of elevated EF Ca with high particle contents and rain pH values in spring. Although the data of air-mass trajectory are still not available at present due to the financial difficulties, meteorological information indicates that air masses of these rain events (elevated pH and EF Ca) originate and/or come from Siberia/Mongolia and Northwest China in relation with the increase of wind strength and development of Siberian/Mongolian cyclones/anticyclones and downward transport of momentum from upper westerlies. Indeed the frequency and strength of both climatic front and cyclone increase in spring. Our observations provide the evidence that elevated particle concentration, pH and EF Ca of rainwaters in spring are due to the contribution of soil dusts from deserts and Gobi (Siberia, Mongolia, and Northwest China) of North Asia. Rapid increases of temperature and evaporation (transpiration) result in that soil is quite dry and loose in spring with quite poor vegetation. Consequently, dust storms are not uncommon in North China during this season. As an example shown, the frequency of the dust storm may reach 10–30 days per year in North China (Sheng et al., 1986). Soil particles from the deserts and exposed regions are initiated into the air and enrolled into the westerlies and then transported eastward over the North Pacific Ocean. Examples are available to help understand the influence of wind-dust with different origins upon the chemical compositions of atmospheric precipitation:

Example no. 1. 90–15 rain event (3 August 1990). The rainfall was 50.0 mm, with the particle content of 2.8 mg l^{-1}. The pH value of rain water decreased to 4.21 and the EF Ca was 16.3 (Table 1). The meteorological information shows the tracjectory of the airmass from southwest of the China (southwest monsoon). Low rain pH values is presumably due to the atmospheric pollution.

Example no. 2. 91–19 rain event (14 May 1991). The rainfall was 10.0 mm, with the particle content of 148.2 mg l^{-1}. The pH value of rain water reached 6.71, and the EF Ca was 211.7. Following the meteorological data, the air-mass responsible was originally from the Mongolia and Xinjiang (Northwest China) (Table 2).

Indeed, EF Ca is positively related to the rain pH with correlation coefficient of $r = 0.60$ in the 1988–1991 observations, whereas correlation between EF Ca and rainfall (mm) is quite poor ($r = -0.25$) (Fig. 4). Our observations suggest the dependence of rain acidity upon the chemistry of major cations (e.g., Ca^{+2}) in wet deposition to the Northwest Huanghai, which is what we found later from the laboratory experiments.

3.2. *Laboratory approach*

Influence of wind-dust from arid regions (e.g., Sahara and Gobi, etc.) on the rain acidity has been observed from other areas of North Hemisphere, such as the Mediterranean Sea (Loye-Pilot et al., 1986). The mechanisms proposed are the acid-base balance regulation by both carbonate and ammonium (Loye-Pilot, et al., 1986; Zhao and Sun, 1986; Iwasaka, et al., 1988; Winchester and Wang, 1989), i.e.,

$$CaCO_3 + 2H^+ = Ca^{2+} + H_2O + CO_2, \quad (2)$$

$$NH_3 + H^+ = NH_4^+, \quad (3)$$

where acids are H_2SO_4 and/or HNO_3. Elevated EF Ca values in this study might give an insight of rain acidity regulation by $CaCO_3$. Chemical analysis shows that wind-dusts in spring contains 10–20% of $CaCO_3$. Similarity of mineral assemblages of wind-dust to soils from Northwest of China (e.g., loess and desert) has also been found (Liu et al., 1980).

The rain water that one obtains at the land stations is not a starting medium but a reaction product. Regulations of atmospheric water (e.g., cloud) acidity may take place before rain drops on to the earth surface. However chemical compositions of rain are highly variable, depending upon the airmass origins and trajectories. Moreover, mixing of different airmasses may occur in the atmosphere before rain drops, and rain water and dusts inside may have quite different origins. This is the rationale to study the acid-base balance of the rain with laboratory models. The results of laboratory simulation indicate rapid increase of both Ca^{+2} and pH during the first 3 h when the

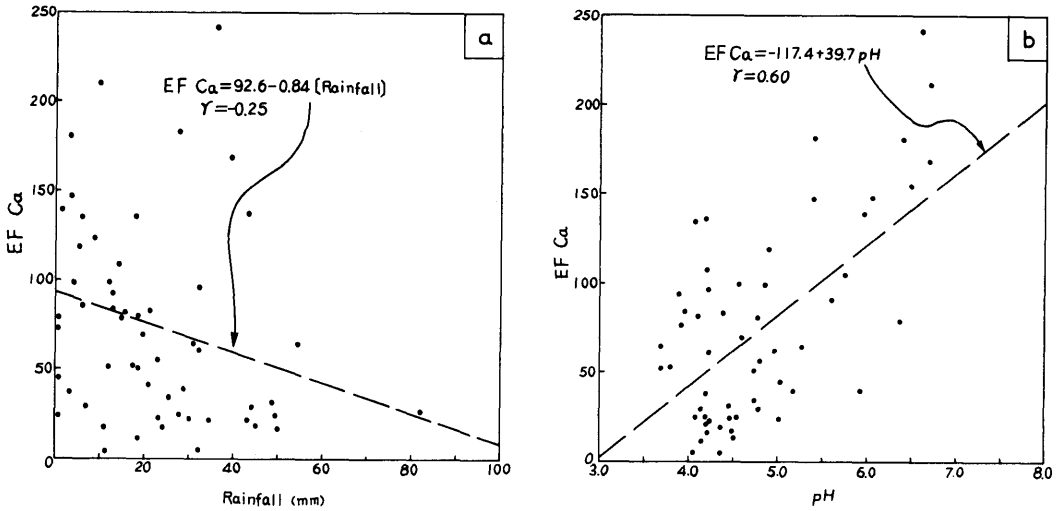

Fig. 4. Plots of the relationships among EF Ca, pH and rainfall. Note that EF Ca is closely related to rain pH ($r = 0.60$), whereas the correlation ($r = -0.25$) between EF Ca and rainfall is quite poor. (a) EF Ca-rainfall (mm); (b) EF Ca-pH.

soil dust was put in rain water (Fig. 5). This is true for both natural and artificial samples. The data indicate that rain acidity may be regulated through $CaCO_3$ dissolution which consumes proton (H^+) of rain water. The variation of NH_4^+ is not as significant as that of Ca^{+2} (Fig. 5). $[\Delta Ca^{+2}/\Delta NH_4^+]$ (ratio of equivalent concentration changes) was $\simeq 4$ for natural rain and $\simeq 6$ for artificial rain samples in the experiments. The stoichiometrical calculation (mass and charge balances) indicates that increase of Ca^{+2} and NH_4^+ may account for 100–110% of proton con-

Table 3. *Flux of atmospheric fallout over the Huanghai (Yellow Sea)*

(a) *Observation data*

Period	Net deposition ($g\,m^{-2}\,yr^{-1}$)	Dry deposition ($g\,m^{-2}\,yr^{-1}$)
December 1989–May 1989	16.3	39.7
June 1989–November 1989	4.9	7.0
December 1989–May 1990	5.9	42.1
June 1990–November 1990	4.0	7.7
December 1990–May 1991	14.9	6.8

(b) *Average deposition*

Period	Wet deposition ($g\,m^{-2}\,yr^{-1}$)	Dry deposition ($g\,m^{-2}\,yr^{-1}$)	Total depositions ($g\,m^{-2}\,yr^{-1}$)
December–May	12.4	29.5	41.9
June–November	4.5	7.3	11.8
whole	16.9	36.8	53.7

Note that dry deposition is generally more important than wet deposition in carrying wind-dust especially in drought years. Elevated flux of wind-dust ($g\,m^{-2}\,yr^{-1}$) occurs in Spring and Winter (December–May), which may be a factor of 3 higher than that in the Summer and Autumn (June–November) each year.

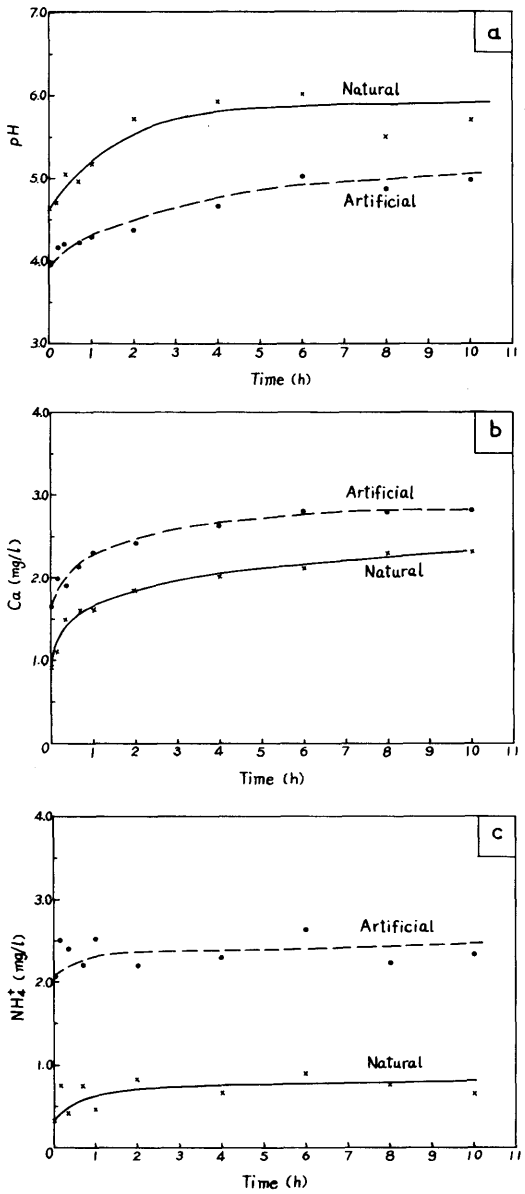

Fig. 5. Laboratory simulation systems. The data show the variabilities of pH, Ca^{+2} and NH_4^+ when soil dusts were put in the natural and artificial rain waters. (a) pH; (b) Ca^{+2} ($mg\,l^{-1}$); (c) NH_4^+ ($mg\,l^{-1}$).

sumption in natural rain and 80–90% of artificial rain. It can be concluded that when dusts were enrolled in acid rain, the dissolution of $CaCO_3$ is of first importance in regulating the rain pH values and hence provides huge EF Ca.

High particle contents in atmospheric precipitation have been observed in both winter and spring. However, winter and spring samples differ in EF Ca and pH values (Fig. 2). Extensive coal consumption for domestic and industrial uses (e.g., central heating) takes place in North China in winter. Coal burning fly ash and SO_2 plus NO_x are emited in to the atmosphere. Aerosol concentrations in winter may be a factor of 2–3 that in summer, and SO_2 content in winter can be two orders of magnitude higher than that of summer time (Zhao and Sun, 1986). Statistical data show that coal-burning fly-ash may account for 60% of total suspended particle concentrations in air with SO_2 emission of $1.5–2.0 \times 10^5$ tons yr^{-1} (Zhao and Sun, 1986). These SO_2 and NO_x emissions may dramatically decrease pH values of atmospheric precipitation and the buffering capacity of coal-burning fly-ash is expected to be weaker than that of soil dusts. Furthermore, in winter, the land is frozen and/or covered with snow, and long-distance transport of soil dusts from exposed areas is largely limited. Hence the high aerosol content with low pH and EF Ca values of atmospheric precipitation in winter appears to be related in part to the anthropogenic activities (e.g., coal combustion) in North China. The results of laboratory approach could explain the high pH value and elevated dust content of rain events in spring, since the dust storms are quite frequent in North China and the cold front systems carry the soil dusts eastwards/southeastwards. Humid air masses are continually transported northeastwards by southwest monsoons in this period. These soil dusts are of high buffering capacity due to abundant carbonates. When enrolled in to the rain clouds, the soil dusts could increase rain pH though acid-base regulation and hence eliminate the harmfulness of acid depositions.

3.3. *Deposition flux*

Based on the observations over $2\frac{1}{2}$ years, wet and total depositions of atmospheric dust fallout (ADF) can be calculated following the formula below:

$$\mathrm{ADF} = \sum C_i \times T_i, \tag{4}$$

where C_i = concentration of particles in rainwater ($g\,m^{-3}$), T_i = rainfall ($\times 10^{-3}$ m).

Dust concentrations in two samplers were obtained separately (with eq. (4)) after individual rain/snow events to get wet (A) and total (B) depositions. Differences in flux between A and B provide an estimate of dry deposition. The results are shown in both Fig. 6 and Table 3. Deposition fluxes are highly variable (including both seasonal and interannual variations). Seasonal wet and dry deposition fluxes of dusts ranged from 4 g m^{-2} yr^{-1} to 16 g m^{-2} yr^{-1} in June–November and from 7 g m^{-2} yr^{-1} to 42 g m^{-2} yr^{-1} in December–May, respectively (Table 3). Furthermore, higher dust fluxes were observed in 1989 and 1990 compared to the data in 1991. Patterns of the atmospheric fall-out over the China Sea can be summarized as elevated flux in the spring and winter in comparison with low values in summer and autumn. This is true for both wet and total depositions. The daily wet and total dust fluxes in spring may be one order of magnitude or even higher compared with summer values (Fig. 6). The highest atmospheric dust flux appears exclusively in spring corresponding to the sporadic wind storms in North China. Actual atmospheric depositions of wind dust to the China Sea average 53.7 g m^{-2} yr^{-1} of which wet deposition accounts for 30–40% (Table 3). It seems that dry deposition is the main pathway of mineral aerosols to the China Sea. Monthly average atmospheric dust flux of wet deposition seldom exceeds 50% of total deposition, suggesting that the wash-out effect is limited compared to the open ocean (e.g., North Pacific). Moreover, the contribution of wet deposition increases in spring and winter, when the particle content in air is quite high and the rainfall is small. The wash-out of wet deposition therefore depends upon the frequency of rainfall and aerosol concentrations in atmosphere.

Table 4 tabulates some typical values of wind-dust flux to the world oceans in North Hemisphere. It is obvious that high atmospheric flux of dusts to the ocean appears over the continental shelf regions close to the Asia and North Africa (Sahara), where values of dust flux may be one order of magnitude higher than those from the deep ocean areas. These two regions are

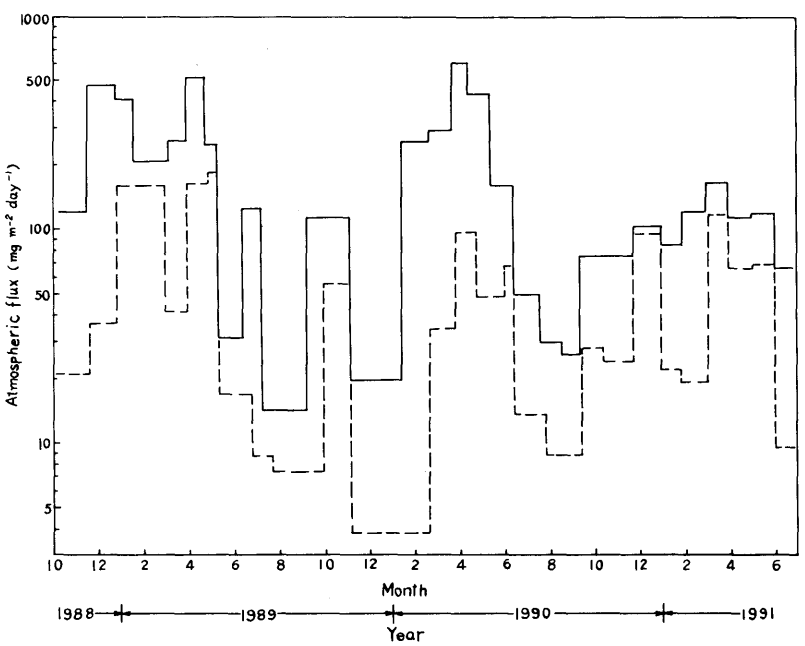

Fig. 6. Calculated daily wet and total dust flux (mg m^{-2} day^{-1}). Note that dust flux in winter and spring may be two orders of magnitude those in summer and autumn. High daily dust flux occurs exclusively in spring in response to the increase of cyclone/anticyclone activity during this period each year. Solid line: bulk deposition; dashed line: wet deposition.

Table 4. *Comparison of wind-dust flux ($g\ m^{-2}\ yr^{-1}$) over some representative regions of world ocean*

Region	Dust flux ($g\ m^{-2}\ yr^{-1}$)	Ref.
Huanghai (Yellow Sea)	53.7	this study
Mediterranean Sea	16.6	(Löye-Pilot et al., 1986)
North Pacific Ocean	5.28	(GESAMP, 1989)
North Indian Ocean	7.08	(GESAMP, 1989)
North Atlantic Ocean	4.03	(GESAMP, 1989)
global total	2.42	(GESAMP, 1989)

Note that high values of dust flux appear in approximation to the Asia (China) and North Africa (Sahara), where they may be one order of magnitude and a factor of 4–5 those from North Pacific and Atlantic Oceans respectively.

also considered to be major sources of mineral aerosols over the world oceans (Uematsu et al., 1983; GESAMP, 1989). Comparison of the data in Table 4 suggests rapid deposition of wind-dusts once they are removed from the source region, i.e., these wind-dusts are released in the shelf regions. Considering the mechanisms affecting the transport of wind-dust, one would expect most of the large mineral particles to be deposited relatively close to the coast because of their high settling velocities and mixing with marine aerosols (wind dusts may be the nuclei of rain drops). Hence aerosol concentrations will drop rapidly during the early stages of transport. Further to the ocean, the primary mechanism of removal should be wet precipitation (Uematsu et al., 1983). Our observations indicated that the main pathway to remove dust is dry deposition; whereas over the North Pacific, flux of wet deposition is twice that of dry deposition (GESAMP, 1989).

4. Summary and conclusion

This study describes the major characteristics of atmospheric depositions over the Huanghai and their geochemical consequences. Emphasis is given to the origin, variation and flux of wind-dust from China to the Northwest Pacific coastal areas. High concentrations of wind-dusts in rain/snow and poor rainfall occur in spring and winter in comparison with abundant rainfall and low dust concentrations in summer and autumn. However samples from winter and spring differ in pH and EF Ca values. Relatively low pH and EF Ca of winter samples are attributed to the impact of atmospheric pollution, whereas high pH and dust concentrations and elevated EF Ca values in spring result from the sporadic dust storms and long-distance transport of alkali soil dusts from exposed areas (e.g., Gobi and loess) of Siberia/Mongolia and Northwest of China. Influence of wind-dust from remote areas upon the rain acidity is quite evident, especially in spring when the activities of anticyclone and cyclone increase. Both in situ measurements and laboratory studies show the regulation of rain pH (acid-base balance) through dissolution of carbonate in acid rain which can dramatically change the chemical compositions of rain water. Our estimated wind-dust flux averages 50–60 $g\ m^{-2}\ yr^{-1}$, which is one order of magnitude higher than that over the Central North Pacific Ocean. This study indicates rapid removal of wind-dusts over the continental shelf at least in the lower part of troposphere.

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