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Interpreting ^{137}Cs depth profiles with no single peak in lake deposits in China

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Abstract ^{137}Cs depth profiles lacking the characteristic peak associated with the period of peak fallout in the early 1960s are reported for a number of lakes in China and reasons for their unusual profile shapes are presented. Uniform ^{137}Cs depth profiles are found in the deposits of most glacial lakes, because the annual ^{137}Cs inputs since 1963 to the lakes from the glaciers in the catchments via melt runoff are controlled primarily by the velocities of the glaciers, which have changed little over recent decades. Uniform ^{137}Cs depth profiles are also frequently found in shallow lakes, because the sediment deposits on the lake bottom are prone to human disturbance. The so-called 1974 and 1986 ^{137}Cs peaks found in the profiles from two lakes in Yunnan Province are not true ^{137}Cs peaks, but represent "mirror image peaks" caused by the low ^{137}Cs concentrations associated with sediment deposited in years with low erosive precipitation immediately prior to 1974 and 1986.

Key words caesium-137; China; depth distribution; lake deposits

INTRODUCTION

Caesium-137 (^{137}Cs) is a man-made fallout radionuclide with a half-life of 30.2 years that is present in the global environment, primarily as a result of the atmospheric testing of nuclear weapons in the late 1950s and early 1960s. The ^{137}Cs aerosols produced by weapons testing were transferred into the stratosphere and the associated fallout was globally distributed. The temporal pattern of annual fallout was broadly similar across the globe and closely related to the intensity of weapons testing. Significant fallout was first recorded in the mid 1950s, maximum fallout occurred in the early 1960s, and fallout declined rapidly through the mid and late 1960s and early 1970s as a result of the nuclear test ban treaty imposed in 1963. The ^{137}Cs deposition flux contributed by the Chernobyl disaster occurring in 1986 was limited in East Asia (Fig. 1), and very much less than in some parts of Europe.

The expected ^{137}Cs depth profile, characterized by a single well-defined peak in ^{137}Cs activity for 1963, has been documented for many lakes in China (Fig. 2(a)). However, uniform depth distributions of ^{137}Cs corresponding to the period since 1963 have been reported for several glacial lakes (Fig. 2(b),(c)) and for some shallow lakes impacted by extensive human disturbances (Fig. 2(d),(e)), and profiles with multiple ^{137}Cs peaks have been reported for some lakes in Yunnan Province (Fig. 2(f),(g)). This contribution attempts to account for these non-standard ^{137}Cs profiles reported for lakes in China.

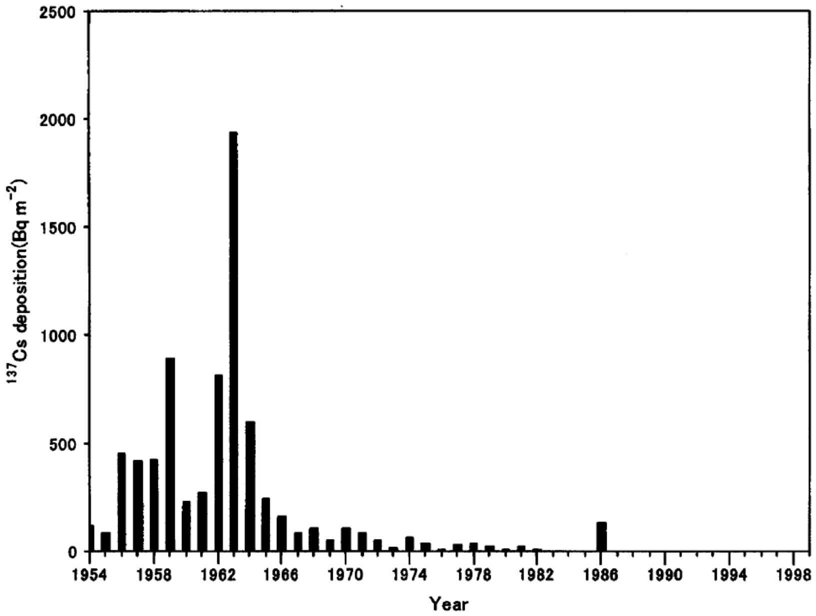

Fig. 1 The annual ^{137}Cs deposition flux record for Tokyo, Japan.

UNIFORM ^{137}Cs DEPTH DISTRIBUTIONS

The ^{137}Cs depth profiles recorded in the deposits of two glacial lakes in China are shown in Fig. 2(b),(c). Lake Cuoe, located in the central Tibetan Plateau, has an area of 61.3 km^2 and a water surface elevation of 4520 m. It is a semi-salt lake with a water salinity of 12.06g l^{-1}. ^{137}Cs is first detected at a depth of 17.0 cm, and the concentration rapidly increases to 30.0 Bq kg^{-1} at the depth of 10.2 cm, and then varies between 20 and 30 Bq kg^{-1} up through the profile. ^{137}Cs is generally evenly distributed throughout the top 10.2 cm of the profile. The depths of 10.2 cm and 17.0 cm in the profile have been related to deposition occurring in 1963 and 1954, respectively (Wu *et al.*, 2001).

South Hongshan Lake, located at the southern foot of the Western Kuanlun Mountains in the northwest of the Tibetan Plateau, has an area of 3.35 km^2 and a water surface elevation of 5060 m. It is also a semi-salt lake with a water salinity of 9.4 g l^{-1}. ^{137}Cs is first detected at a depth of 42.0 cm, and the concentration rapidly increases upcore to 20 Bq kg^{-1} at a depth of 30.0 cm, and then gently increases to 35 Bq kg^{-1} at 6.0 cm depth. Concentrations show little variation within the upper 6.0 cm of the profile. Generally, ^{137}Cs concentrations increase slightly upcore in the top 30.0 cm of the profile. The depths of 30.0 cm and 42.0 cm in the profile were related to deposition occurring in 1963 and 1954, respectively, by Zhu *et al.* (2002). Unlike the normal single ^{137}Cs peak shape encountered in most lakes, the ^{137}Cs depth profiles in glacial lakes are characterized by a generally uniform distribution in the upper part of the profile deposited since 1963. The cause of these uniform ^{137}Cs concentrations in the recent sediment deposited since 1963 requires further explanation.

A tentative explanation of the generally uniform ^{137}Cs depth distribution since 1963 found in sediment profiles from glacial lakes is provided below (cf. Fig. 3). ^{137}Cs aerosols deposited on the glacier surfaces during the period of nuclear weapon testing from the mid 1950s to the 1970s will have been preserved in the ice layers of that period.

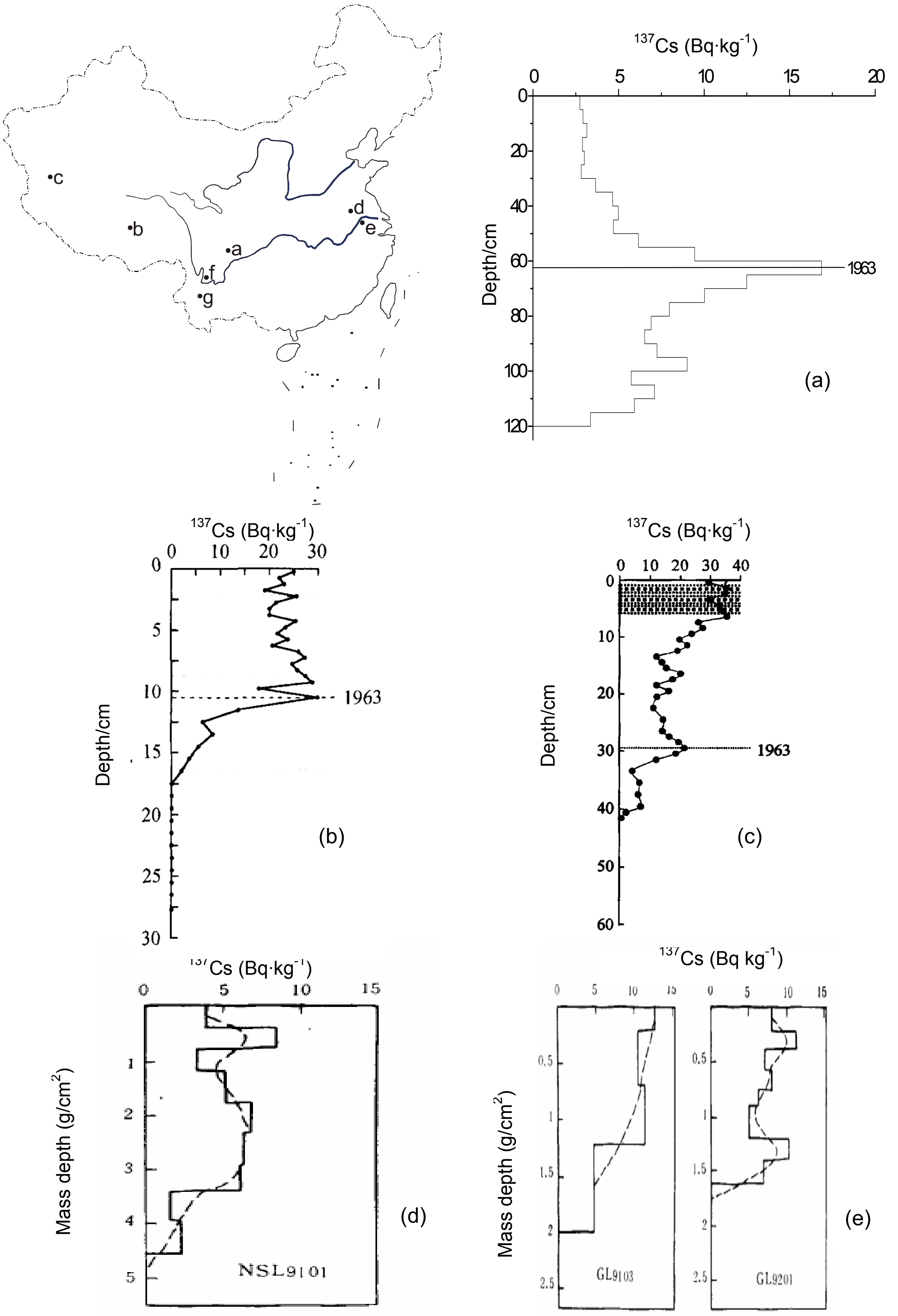

Fig. 2 Cs^{137} depth distribution profiles for lakes in China: (a) Wujiagou Reservoir; (b) Lake Cuoe; (c) South Hongshan Lake; (d) Lake Nushan; (e) Gucheng Lake; continued opposite.

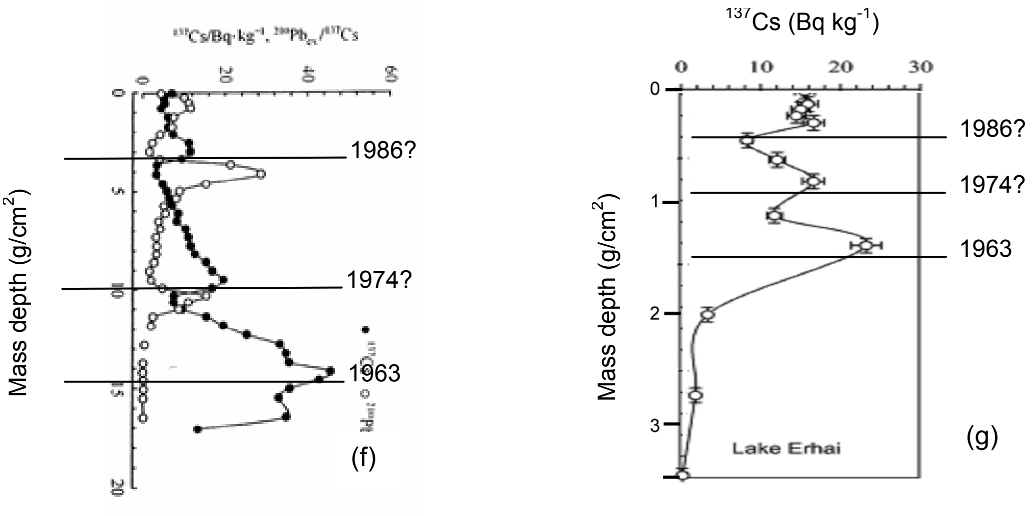

Fig. 2 continued ^{137}Cs depth distribution profiles for lakes in China: (f) Chenghai Lake; and (g) Erhai Lake.

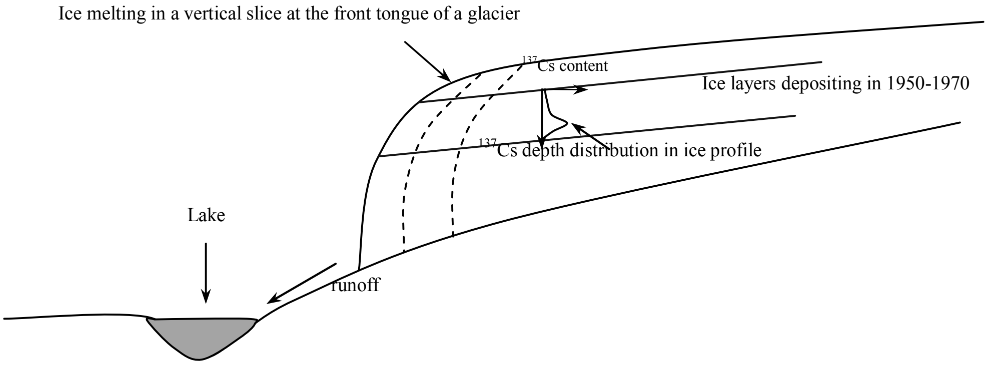

Fig. 3 The mechanism for delivering of ^{137}Cs aerosols deposited in the ice layers of a glacier into a downstream lakes by meltwater runoff.

Changes in the ^{137}Cs concentrations in ice in a depth profile of a glacier are generally well correlated with the fluctuation of the ^{137}Cs deposition flux and have a single well-defined ^{137}Cs peak (Fig. 3). ^{137}Cs aerosols first appeared in the 1954 ice layer and the concentrations subsequently increased rapidly, reaching a maximum in the 1963 layer, then sharply decreased to below detection after 1970. When the ice layers containing ^{137}Cs aerosols melt at the glacier front, the radiocaesium will be delivered to the downstream lake with the runoff from the melting ice. The melting of a glacier predominately occurs at the glacier front and the annual meltwater discharge is mainly determined by the velocity of the glacier. Therefore, the amount of ^{137}Cs delivered each year to the downstream lake with melting runoff should be related to the velocity of the glacier and can therefore be expressed as follows:

$$W_{Cs} = A_{Cs} \times B \times L \qquad (1)$$

where W_{Cs} is the annual ^{137}Cs yield from a glacier (Bq year^{-1}); A_{Cs} is the ^{137}Cs inventory of the glacier (Bq m^{-2}); B is the average width of the glacier (m); and L is the velocity of the glacier (m year^{-1}).

As the current glacier velocity can be viewed as relatively constant for most glaciers, the annual ^{137}Cs yield from the glacier should be nearly constant. Since the sediment deposition rate is also likely to be relatively constant in recent years, ^{137}Cs concentrations in the deposits should show little change since 1963 and the ^{137}Cs depth profile should have a relatively uniform shape for most glacial lakes, such as the Cuoe Lake. The significant upcore increase in ^{137}Cs concentration since 1963 in the South Hongshan Lake can be explained in terms of the accelerated melting of the glaciers within the catchment, which is probably linked to recent climatic warming.

Similar uniform ^{137}Cs depth profiles have also been reported for two shallow lakes in China by Xia *et al.* (1995) and Xiang *et al.* (1996) (see Fig. 2(d),(e)). Nushan Lake, located in Jiashan County, Anhui Province, has an area of 97.0 km^2 and a maximum water depth of 3 m. Gucheng Lake, located in Gaoxun County, Jangsu Province, has an area of 24.5 km^2 and a maximum depth of 6.5 m. The ^{137}Cs concentrations in the depth profiles from Nushan Lake mostly vary between 4.0 and 6.5 Bq kg^{-1} within the top portion of the profile, above a mass depth of 4.5 g cm^{-2}, whilst for Gucheng Lake the concentrations within the upper part of the profile, above a mass depth of 1.6 g cm^{-2} mostly vary between 5.0 and 10.0 Bq kg^{-1}. These two shallow lakes are both located in densely populated areas of East China and the sediment deposits on the lake bottom are prone to disturbance by human activities, such as fishing, harvesting aquatic plants, and boating etc. It would seem reasonable to suggest that the uniform ^{137}Cs depth distributions within the upper few centimetres of the sediment deposits in the two lakes are caused by human activities.

MULTIPLE ^{137}Cs PEAKS IN THE PROFILE

In addition to the 1963 peak, two other ^{137}Cs peaks ascribed to 1974 and 1986 were identified and reported by Wan *et al.* (2001, 2004) for Chenghai and Erhai Lakes in Yunnan Province, China (Fig. 2(f),(g)). The former has an elevation of 1500 m, a water surface area of 77.2 km^2 and average water depth of 25 m, and the latter has an elevation of 1972 m, a water surface area of 248 km^2 and an average water depth of 10 m. In the sediment profile for Chenghai Lake, ^{137}Cs is first detected at a mass depth of 17 g cm^{-2} and concentrations rapidly increase upcore towards the maximum concentration of 48 Bq kg^{-1} at a mass depth of 14 g cm-^{2}. Above this depth, concentrations decrease sharply up to a mass depth of 11 g cm^{-2}. In the upper layer above a mass depth of 11 g cm^{-2}, ^{137}Cs concentrations vary between 8 and 21 Bq kg and have a general tendency to decrease, but with two small pulses occurring at depths of 9.5 and 3.0 g cm^{-2}, respectively. The Erhai Lake profile has a similar shape in which ^{137}Cs is detected at the mass depth of 3.5 g cm^{-2} and the maximum concentration of 24 Bq kg^{-1} occurs at the mass depth of 1.5 g cm^{-2}. In the top layer of 0–1.5 g cm^{-2} mass depth, ^{137}Cs concentrations vary between 8 and 17 Bq kg^{-1} and have no clear tendency to decrease upcore and two small pulses are clearly evident at mass depths of 0.8 and 0.3 g cm^{-2}, respectively. It is questionable to link these two ^{137}Cs peaks to the nuclear weapon testing in 1974 and the Chernobyl disaster in 1986, because the ^{137}Cs deposition records for Tokyo, Japan (Fig. 1), provide no evidence for a 1974 fallout peak and show that the 1986 ^{137}Cs fallout peak caused by the Chernobyl disaster accounts for only 2.5% of the total ^{137}Cs deposition inventory at Tokyo (Aoyama, 1986) and would not be reflected in the sediment profile. Other explanations for the fluctuations evident in the ^{137}Cs depth profiles of the two lakes since 1970 must be sought.

The changes in the ^{210}Pb$_{ex}$/^{137}Cs ratio in the profile from Chenghai Lake provide a clue as to a possible explanation for the two ^{137}Cs peaks wrongly attributed to 1974 and 1986 (Fig. 2(f)). The ^{210}Pb$_{ex}$/^{137}Cs ratio peaks just below the two ^{137}Cs peaks. The ^{137}Cs and ^{210}Pb$_{ex}$ radionuclides in the lake deposits are not only derived from direct deposition on the lake surface, but also reflect catchment-derived inputs associated with sediment mobilized from the catchment surface and transported to the lake. The fluctuations in ^{137}Cs concentration in the upper part of the sediment profile could result from the changes of the relative contributions of sediment from different sources in the catchment after 1970, because there has been very little direct fallout input of ^{137}Cs to the lake surface since 1970 and any ^{137}Cs found in the sediment deposited after 1970 will have been primarily catchment-derived. Since the annual ^{210}Pb$_{ex}$ deposition flux from the atmosphere can be viewed as nearly constant, the fluctuations of ^{210}Pb$_{ex}$ concentration in the sediment profile will reflect changes in the sediment deposition rate in the lake. The higher the ^{210}Pb$_{ex}$ concentration, the lower the sediment deposition rate. The two peaks in the ^{210}Pb$_{ex}$/^{137}Cs ratio in the upper part of the sediment profile reflect low sediment deposition rates in those years. Changes in contemporary sediment deposition rates in a lake are usually caused by variations in precipitation amounts, if land use in the catchment has not changed. The low sediment deposition rates indicate periods of low precipitation for the two lakes. Precipitation variations frequently result in the changes in the relative contributions of sediment from different sources in a catchment. It is suggested that the relative contributions of sediment derived from surface erosion were less in the years with low precipitation than in normal years, and that the ^{137}Cs concentrations in the sediment deposited in those years were also lower than in normal years, because sediment contributed by surface erosion will have a higher ^{137}Cs concentration than sediment mobilized by subsurface erosion. The two ^{137}Cs peaks in the upper sediment profile, erroneously attributed to 1974 and 1986, are therefore probably not real ^{137}Cs peaks but "mirror image peaks" produced by the low ^{137}Cs concentrations associated with sediment deposited in the in the previous year.

CONCLUSION

Caesium-137 depth profiles without the characteristic single peak have been found in several lakes in China. It is important to recognize that downcore changes in ^{137}Cs concentration in lake deposits will be related not only to variations in the ^{137}Cs deposition flux from the atmosphere, but also to variations in the catchment-derived ^{137}Cs input to the lake (cf. Walling & He, 1992). For glacier lakes, the annual ^{137}Cs input from the glaciers in the catchment associated with glacier melting will have been determined primarily by the flow velocity of the glacier since 1963. As glacier velocities are currently relatively stable, the ^{137}Cs depth distributions in the recent sediment deposits in glacial lakes are likely to be quite uniform. Uniform ^{137}Cs depth distributions are also often found in shallow lakes because the surface layers of the sediment deposits are prone to human disturbance. The two ^{137}Cs peaks in the profiles from two lakes in Yunnan Province, which have been erroneously attributed to 1974 and 1986, are not real ^{137}Cs peaks but "mirror image peaks" reflecting the low ^{137}Cs concentrations in the sediment deposited in years with low precipitation immediately prior to the "peaks".

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REFERENCES

Aoyama, M., Hirose, K. & Suzuki, Y. (1986) High levels of radioactive nuclides in Japan in May. *Nature* **321**, 819–820.

Walling, D. E. & He, Q. (1992) Interpretation of caesium-137 profiles in lacustrine and other sediments: the role of catchment-derived inputs. *Hydrobiologia* **235**(6), 219–230.

Wan, G., Bai, Z. & Liu, T. (2001) The differential fallout of ^{137}Cs between western Yunnan and central Guizhou: implications for the barrier effect of the Qinghai-Xizang uplift on global atmospheric pollutants in the Yunnan Guizhou plateau. *Quatern. Sci.* **21**(5), 407–415.

Wan, G., Chen, J. & Xu, S. (2004) Using sudden increases in ^{210}Pb sediment flux to investigate changes in lake productivity: the case of Chenghai lake, Yunnan, China. *Science in China* (series D) **34**(2), 154–162 (in Chinese).

Wu, Y., Wang, S. & Xia, W. (2001) Environmental variation in the central Tibetan Plateau over the last 200 years. *Science in China* (series D) **44**(Suppl.), 332–337.

Xia, W., Wang, Y. & Pan, H. (1995) Modern sedimentation rate dating and its environmental implication for Nushan lake. *J. Lake Science* **7**(4), 314–320 (in Chinese).

Xiang, L., Wang, S. & Xue, B. (1996) Accumulation and time marker significance of Chernobyl-derived ^{137}Cs in lake sediments from Jiangsu-Anhui. *Oceanologia et Limnologia Sinica* **27**(2), 132–137 (in Chinese).

Zhu, L., Chen, L. & Li, B. (2002) Environmental changes reflected by the lake sediments of the South Hongshang lake, northwest Tibet. *Science in China* (series D) **45**(5), 430–439.