THE IMPACT OF YEAR-TO-YEAR CHANGES IN THE WEATHER ON THE SEASONAL DYNAMICS OF LAKES

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Introduction

The world's climate is changing at an unprecedented rate and climatologists are now convinced that a large part of this change is due to the increased concentration of greenhouse gases (McCarthy et al. 2001). Global air temperature has increased by about 0.6 °C since the beginning of the 20th century with about 0.4 °C of this warming occurring in the last 30 years (UKCIP 2002). 1998 was the warmest year on record and there is mounting evidence that extreme weather events, such as heavy rain, are becoming more common (Osborn et al. 2000). These changes have already had an effect on the dynamics of lakes throughout Europe (Blenckner & Chen 2003; George 2002; Straile 2000) and have important consequences for the way we manage our lakes and reservoirs in the 21st century.

The methods currently used to monitor and model lakes were developed when weather conditions were very different to what they are today. Most are based on samples collected at weekly or fortnightly intervals and cannot quantify the effects of short-term, more extreme, variations in the weather. In this volume we describe how partners from the UK, Spain and Ireland combined their resources to develop new methods for quantifying the impact of changes in the weather on the dynamics of lakes. In this article, I present some examples to show the importance of these investigations using case studies from a number of lakes in the English Lake District.

Changing weather patterns in the English Lake District

The weather in the English Lake District is notoriously variable but systematic trends have recently been identified for a number of climatic variables (George et al. 2000; George 2000). Here, I present two examples to illustrate these trends and then discuss the potential impact of these changes on the dynamics of the lakes. The first example is taken from a

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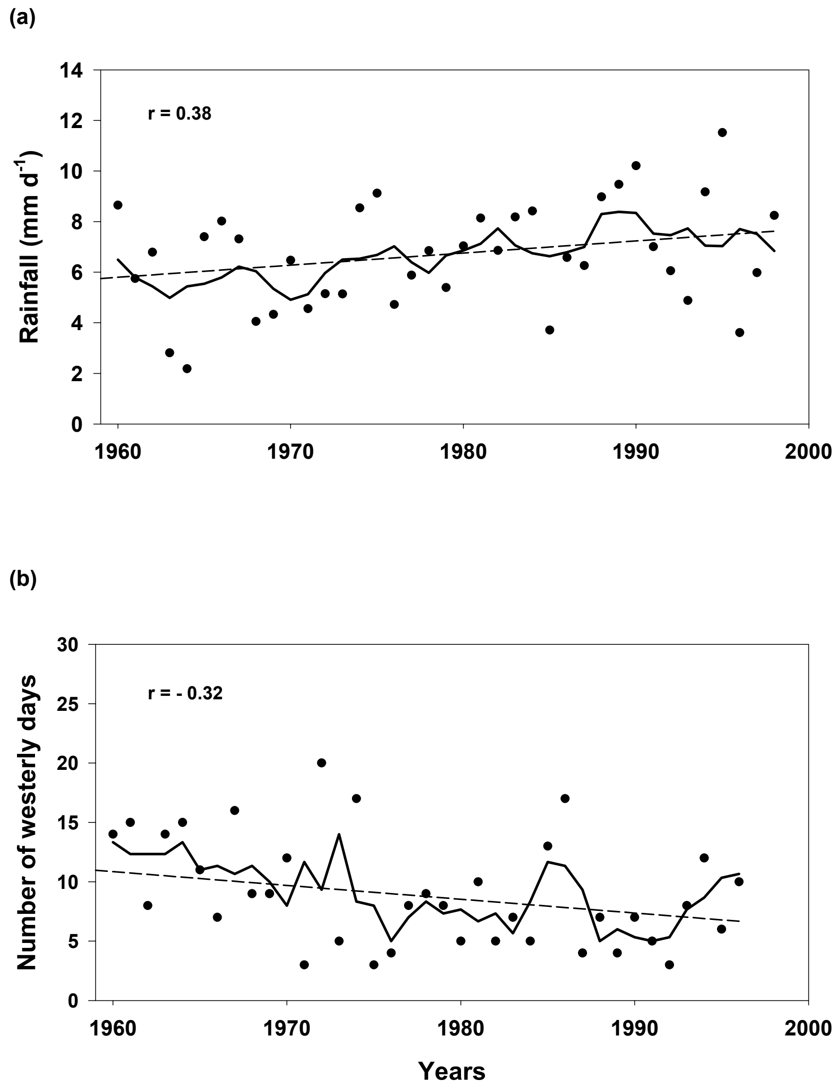

FIG. 1. (a) The year-to-year variations in the average winter rainfall at Ambleside between 1960 and 1996. (b) The year-to-year variations in the number of westerly days recorded in the UK every summer between 1960 and 1998. In each case the points show the averages for the individual seasons and the solid line the three-point running mean.

study of winter conditions in the English Lakes and shows that there has been a significant increase in the average rainfall. The second example is taken from a study of summer weather conditions in the UK and shows there has been a recent decrease in the frequency of westerly winds.

Fig. 1a shows the year-to-year variations in the average winter (December to February) rainfall recorded at Ambleside between 1960 and 1998. These results demonstrate that winters in the area have become very much wetter in recent years. The average winter rainfall recorded in the 1960s was 5.8 mm per day but this increased to 7.3 mm per day in the 1990s. A linear regression fitted to this time-series shows that this trend is statistically significant at the 95 % level. The increase recorded over the period was 1.1 mm which is equivalent to 0.03 mm per day every winter. Periods of very heavy rain also appear to have become more common. In the 1960s, the calculated coefficient of variation for the winter measurements was ca. 20 % but this increased to ca. 30 % in the 1990s. Increases in the rainfall of this magnitude will have little effect on the large lakes, but could have a significant effect on the winter dynamics of small lakes with a short residence time.

The system developed by Lamb (1950) to classify weather types in the UK is now widely used to analyse patterns of change. This system is based on the subjective analysis of daily weather charts and contains eight directional circulation types, three non-directional types and an unclassified category. In summer, the two circulation types that have the most pronounced effect on the weather are the non-directional anticyclonic type (A) and the directional westerly type (W). Anticyclonic days are characterised by very low rainfall, increased temperatures and lower average wind speeds. Westerly days tend to be wetter and cooler with stronger winds blowing from the Atlantic.

Fig. 1b shows the variation in the number of westerly days recorded in the UK every summer between 1960 and 1996. The results demonstrate that there has been a progressive decrease in the number of westerly days. The average number of westerly days recorded in the 1960s was 11.8 but this decreased to 7.7 in the 1990s. A linear regression fitted to this time-series shows that this trend is statistically significant at the 95 % level. The decrease recorded over the period was 3.6 days which is equivalent to 0.1 days every summer. There is also some indication that summer wind speeds are becoming less variable. In the 1960s, the calculated coefficient of variation was 58 % but this decreased to less than 50 % in the 1990s.

The impact of year-to-year changes in the weather on the dynamics of lakes

One of the most effective ways of assessing the impact of changes in the weather on the dynamics of lakes is to compare their response to the conditions encountered in some extreme years. Here, I present two examples to illustrate these effects: the first related to winter rainfall and the second to summer wind speeds.

Example 1: The effect of changes in the winter rainfall on the biomass of phytoplankton in Blelham Tarn

In the smaller lakes of the English Lake District, year-to-year variations in the winter rainfall have a major effect on their residence time, chemistry and biology (Lund 1978; Talling 1993). Blelham Tarn is a small, productive lake situated about 2 km west of Windermere (54° 23’ N; 2° 54’ W). The lake covers an area of ca. 0.1 km^2 and has a mean depth of 6.8 m and a maximum depth of 14.5 m. The data analysed here covers the period between 1964 and 1999, a time when there were large inter-annual variations in the winter rainfall. Daily rainfall measurements were collated from a site a few kilometres north of the lake and estimates of the winter concentration of chlorophyll derived from water samples collected at weekly or fortnightly intervals. ‘Winter’ was empirically defined as the first 10 weeks of each year: a time when the chlorophyll concentration was close to the annual minimum. Water samples for chlorophyll analyses were collected from the lake at weekly intervals using a 5 m length of hose (Lund & Talling 1957) and the pigment extracted using the method described by Talling & Driver (1963).

Fig. 2a shows the relationship between the biomass of phytoplankton in Blelham Tarn and the rainfall, recorded during the first 10 weeks of each year. The results demonstrate that there is a significant negative correlation ($r = -0.52$) between the two variables and the fitted regression is statistically significant at the 99.9 % level. Figs 2b and c show how the variation in the rainfall, recorded in two ‘extreme’ years, influenced the biomass of phytoplankton in Blelham Tarn. In 1987 (Fig. 2b), the mean rainfall recorded during the first 10 weeks of the year was 3.9 mm per day and the mean winter biomass of phytoplankton was 8.7 $\mu g\ l^{-1}$. In 1989 (Fig. 2c), the mean rainfall recorded during the first 10 weeks of the year was 8.2 mm per day and the mean biomass of phytoplankton was reduced to 2.2 $\mu g\ l^{-1}$. The other difference between the two years was the frequency and intensity of the rainfall events. In 1987, there were several days with no rain but in 1989, 40 days of light rain were followed by several consecutive days of very high rainfall.

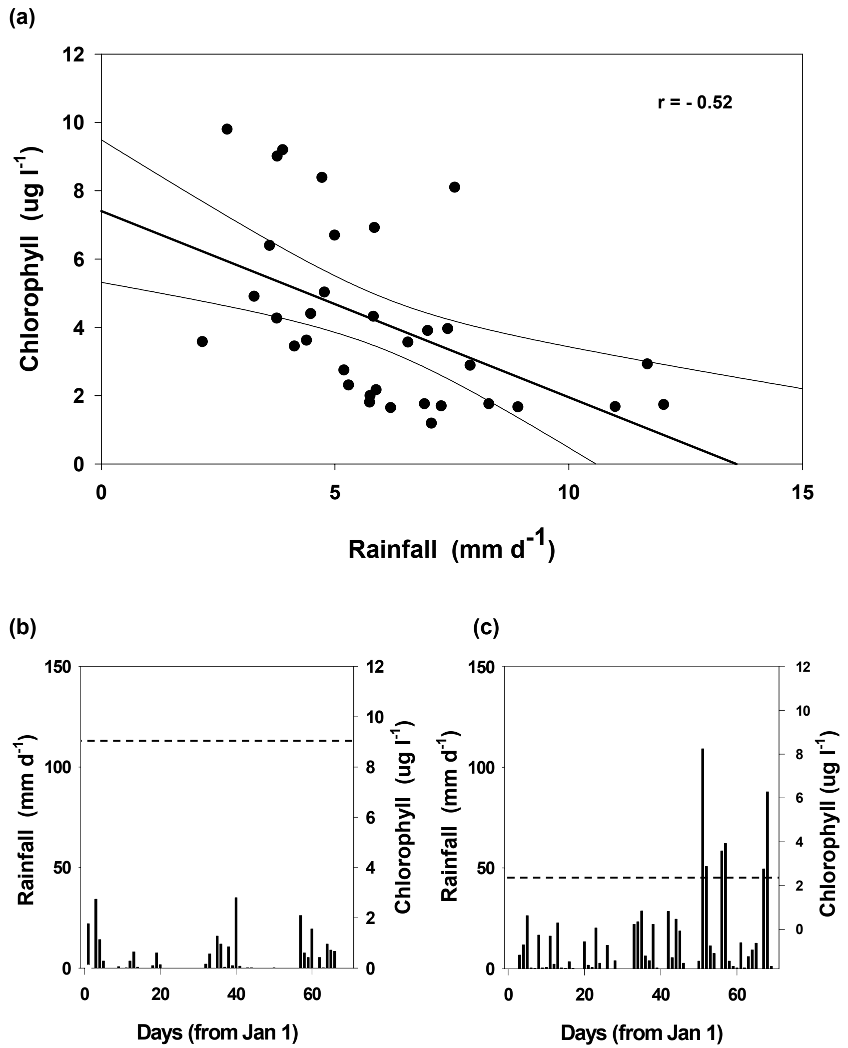

FIG. 2. (a) The relationship between the biomass of phytoplankton in Blelham Tarn and the winter rainfall (1964–1999). The biomass of phytoplankton is given as the concentration of chlorophyll *a* and the 'winter' averages have been calculated for the first 10 weeks of the year. (b) The daily variation in rainfall in a dry winter (1987) when the biomass of phytoplankton was relatively high. (c) The daily variation in rainfall in a wet winter (1989) when the biomass of phytoplankton was relatively low. The broken line shows the mean winter concentration of chlorophyll *a*.

Example 2: The effect of changes in the summer wind-speed on the growth of Cyanobacteria in Esthwaite Water

Esthwaite Water (53° 21' N; 2° 59 W') is one of the most productive lakes in the English Lake District and has been the subject of intensive scientific study for more than 50 years. The lake has a surface area of 1.01 km^2, a mean depth of 6.4 m, a maximum depth of 14 m and usually remains thermally stratified from the end of May until the middle of October. Samples of water for chlorophyll analyses and phytoplankton counts have been collected from the lake at regular intervals since the early 1950s using the methods already described for Blelham Tarn. The pattern of phytoplankton succession in the lake has remained much the same throughout the period of study (Lund 1978; Talling 1993). Early in the year, the phytoplankton community is dominated by the diatoms *Asterionella formosa* Hass. and *Aulacoseira subarctica* (O. Müller). When the lake becomes thermally stratified, the diatoms decline and are replaced by a variety of small flagellates such as *Rhodomonas* and *Chlorella*. Later in the summer, large, slow-growing species that Reynolds (1984) describes as 'stress tolerators' become more abundant. In the early 1970s, the dominant species were the dinoflagellates *Ceratium hirundinella* and *Ceratium furcoides* but these were replaced by the Cyanobacteria (blue-green algae) *Aphanizomenon* and *Microcystis* in the 1980s. These species grow particularly well in warm, calm summers but quite short periods of intense wind mixing can disrupt this growth and return the phytoplankton community to an earlier stage in the seasonal succession.

The simplest way of quantifying the impact of changes in the weather on the mixing characteristics of a lake is to calculate the thermal stability of the water column using the procedure described by Schmidt (1928). When the lake is well mixed, this index is close to zero but it increases to values between 20 and 150 when the lake is thermally stratified. Figs 3a and b compare the seasonal development of the Cyanobacterium *Microcystis aeruginosa* in Esthwaite Water in an unusually windy and a very calm summer. Fig. 3a shows the variation in the stability of the water and the abundance of *Microcystis* in 1980, a year when the summer wind speeds were very high. Small numbers of *Microcystis* were recorded at irregular intervals but the summer phytoplankton community was dominated by flagellates and diatoms. Fig. 3b shows the variation in the stability of the water and the abundance of *Microcystis* in 1983, a year when the summer was warm and exceptionally calm. Very high concentrations of *Microcystis* were recorded in the lake in late summer following six weeks of unusually calm weather.

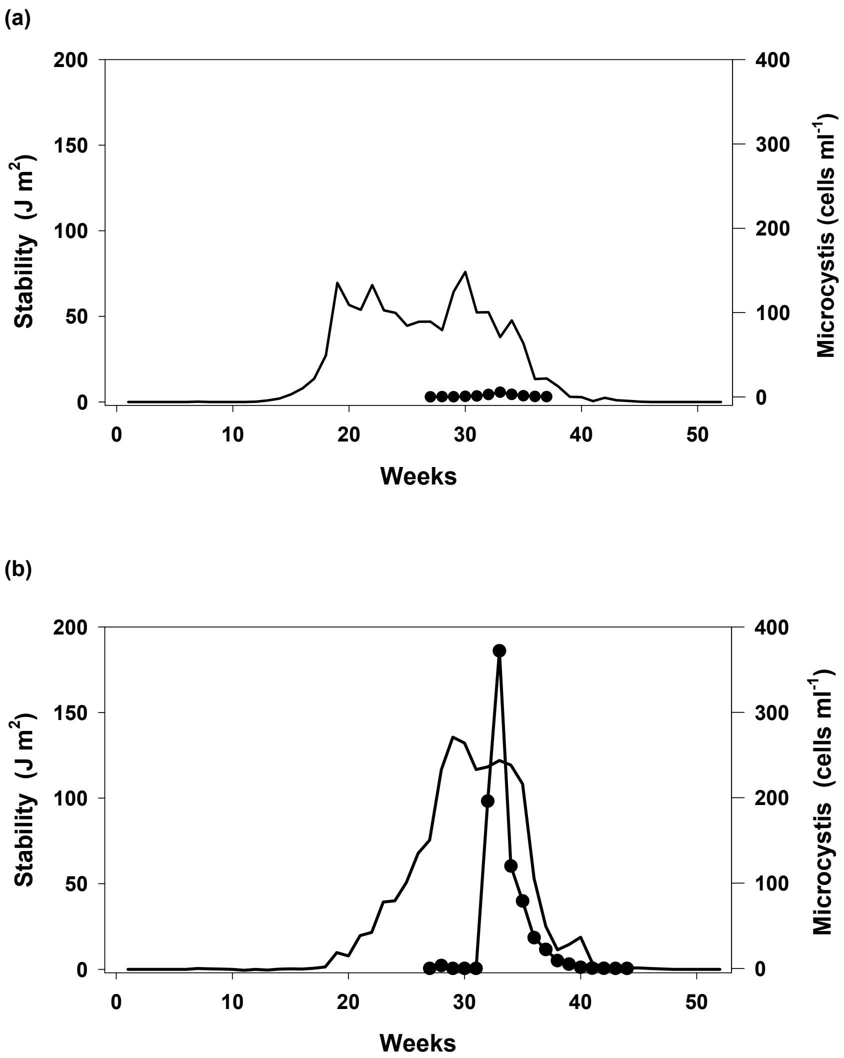

FIG. 3. The growth of the Cyanobacterium *Microcystis* in Esthwaite Water in (a) a windy year, 1980, when the stability of the water column was low, and (b) in a calm year, 1983, when the stability of the water column was high. The solid line is stability and the points are *Microcystis* numbers.

Quantifying the impact of short-term changes in the weather on the dynamics of lakes

In recent years, a number of process-based models have been developed to simulate the responses of lakes to changes in the weather. These range from simple energy balance models like TEMIX (Mironov et al. 1991), to more complex phytoplankton succession models, such as PROTECH (Reynolds et al. 2001). One problem faced by these modellers is the poor quality of the meteorological data used to drive the simulations. In some cases, supporting meteorological measurements are acquired from sites situated some distance from the lake. In others, the instruments are located on the shore of the lake but are sheltered by buildings, trees or the surrounding terrain. The following examples show the extent to which meteorological measurements acquired by instruments moored in open water differ from those acquired by similar instruments located on the shore.

Fig. 4 compares the air temperatures and wind-speed measurements recorded by two stations operating on Esthwaite Water in 1996. One station, the ‘Shore Station’, was located on the roof of a boathouse situated on the west shore. The other, the Automatic Water Quality Monitoring Station ‘AWQMS2’, was located on a buoy moored about 500 m away in the open water. Figs 4a and b show the relationship between the air temperatures measured by the two stations in winter and in summer. The slopes of the fitted regressions were not significantly different from 1, but the individual measurements differed by as much as 3 °C in winter and 4 °C in summer. Figs 4c and 4d show the relationship between the wind speeds recorded by the two stations in winter and in summer. In winter (Fig. 4c), the correlation between the two measurements was high but the slope of the regression was significantly different from 1, i.e. the difference between the measurements increased as the wind speed increased. In summer (Fig. 4d), the correlation between the two measurements was much lower, the slope of the regression was not significantly different from 1 but there was a large positive intercept on the vertical axis, i.e. light winds were being recorded in the open water when no wind was recorded on shore.

Concluding remarks

The examples assembled here explain why those charged with the management of lakes need to pay more attention to the potential effects of both short-term and long-term variations in the weather. Many water quality problems that were once thought to be driven by changes in the catchment are now known to be influenced by changes in the weather that operate on a global scale (George 2002; Straile et al. 2002). The frequency

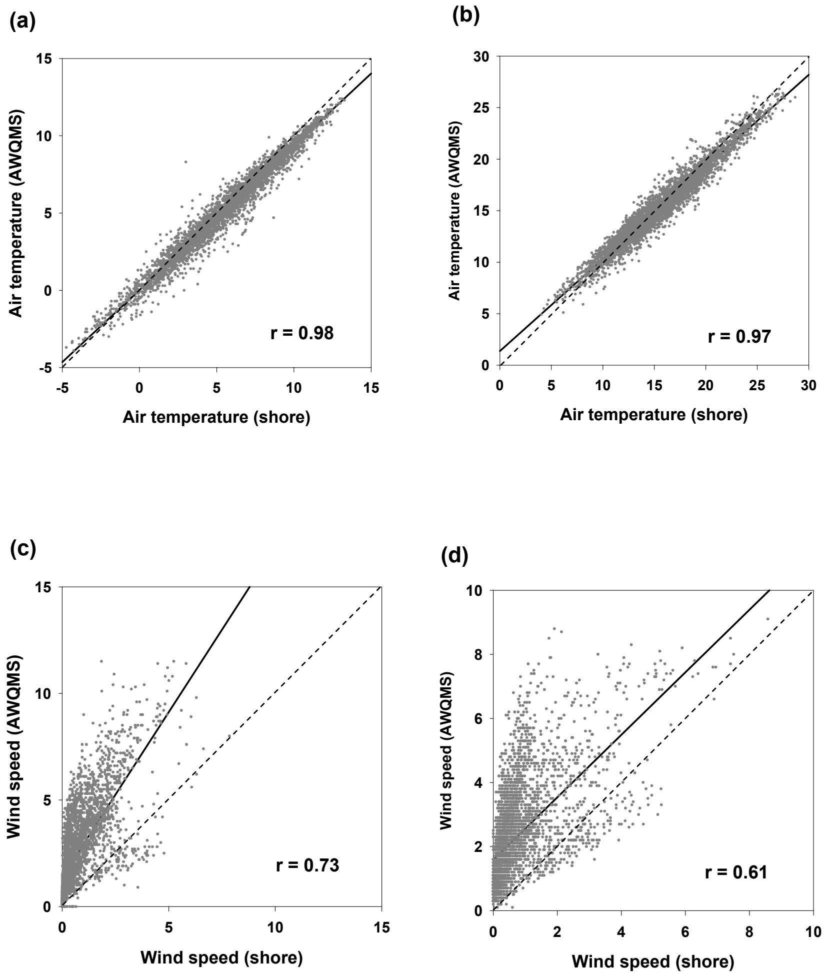

FIG. 4. The relationship between air temperatures at Esthwaite Water measured by the Shore Station and the Automatic Water Quality Monitoring Station in (a) winter and (b) summer. The relationship between the wind speeds measured by the two Esthwaite Water stations in (c) winter and (d) summer. The values plotted are hourly averages; the dotted line denotes the relationship expected if there was no difference between the two stations. All data are from 1996.

of extreme weather events is also predicted to increase in the coming decades. The climate change scenarios produced by the UK Climate Impacts Programme (UKCIP) suggest that summers as dry as 1995 could become common and that there would be a corresponding increase in the number of winter storms. The case studies presented here demonstrate the extent to which year-to-year variations in the weather influence the dynamics of lakes. Thermally stratified lakes are particularly sensitive to such variations since they respond to the combined effects of the sun, the wind and the rain. The consequences of these variations can, however, only be fully understood if the lakes are monitored at frequent intervals for an extended period of time. Unfortunately, the high costs associated with regular sampling have already led to a reduction in many established monitoring programmes. For example, the lakes in the Windermere catchment were once sampled every week but are now only sampled at fortnightly intervals. Automatic instruments of the kind decribed here (Rouen et al. 2005, this volume) cannot replace such regular visits but they can provide useful information on the frequency and intensity of weather-driven events. Automatic stations of this kind are widely used in the marine environment (e.g. SmartBuoy[1], Idronaut Buoy 601 Profiler and Buoy 701 Profiler[2], and YSI Profiling Systems[3]).

In the next article in this volume, Rouen et al. (2005) describe the design, construction and testing of a range of automatic systems that can be used to monitor the responses of lakes and rivers to short term changes in the weather. These instruments have been designed to provide the high-resolution data required by modellers and to meet the operational requirements of lake and reservoir managers.

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[1] Developed by CEFAS (The Centre for Environment Fisheries and Aquaculture Science). See: www.cefas.co.uk/monitoring/SmartBuoy.asp

[2] www.tresanton.co.uk/pdf/601.pdf; www.tresanton.co.uk/pdf/701.pdf; www.idronaut.it

[3] www.ysi.com/extranet/EPGKL.nsf/447554deba0f52f2852569f500696b21/4af0701d606f9c2785256f2a006be743!OpenDocument

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