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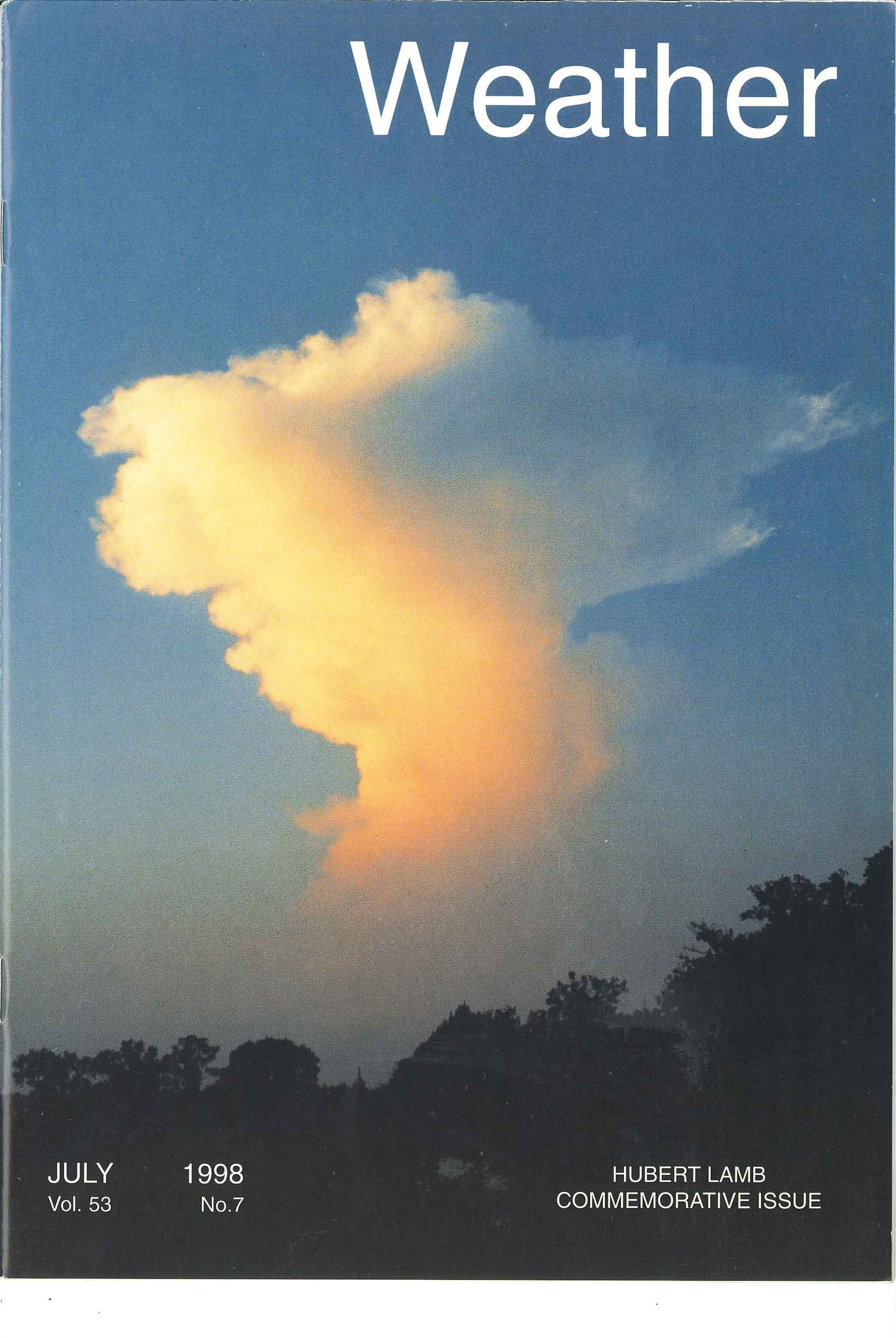

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HUBERT LAMB
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important (Wheeler 1991) but events came to a more decisive conclusion at the Battle of Camperdown on 11 October.

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Correspondence to: Dr D. A. Wheeler, Geography Department, University of Sunderland, Forster Building, Chester Road, Sunderland SR1 3SD.

The contribution of Hubert H. Lamb to the study of volcanic effects on climate

P. M. Kelly[1], P. D. Jones[1], A. Robock[2] and K. R. Briffa[1]

[1]Climatic Research Unit, University of East Anglia

[2]Department of Environmental Sciences, Rutgers University, New Brunswick

On 2 July 1970 the Royal Society published one of Professor Hubert H. Lamb's most significant contributions to climate research, the monograph "Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance" (Lamb 1970). The landmark report contained not only the well known chronology of volcanic eruptions and dust veil index but also an exhaustive review of the scientific basis of the volcanic forcing mechanism and a preliminary analysis of the observational evidence linking climate change and volcanic events. It had long been recognised that the pollution ejected by a major, explosive volcanic eruption could affect weather and climate by modifying the transfer of radiation through the atmosphere. Lamb's achievement was to draw together existing material from a number of disparate fields, initiating currents in climatological research that remain evident today.

The development of Lamb's interest in the subject of volcanic activity and climate can be traced back to the early 1950s. At that time, Lamb was posted to the Climatological Division of the Meteorological Office in Harrow to deal with overseas climatological enquiries. Fortuitously, the Meteorological Office archives, having been parcelled up for safe keeping during the Second World War, were lying, still packaged, in a basement there and Hubert Lamb "led a charmed life for nearly two years" (Taba 1994) uncovering and discovering the wealth of data that they contained. Though this experience played a major rôle in shaping his later research career, the first project that it stimulated was the creation of monthly mean pressure maps for each January and July going back to 1750 (Lamb and Johnson 1966). This work was not to be completed until the end of the decade, but the emerging evidence of significant changes in the atmospheric circulation on the interannual, decadal and longer timescales led to the inevitable question of what had caused these changes in climate. In Lamb's own words, "volcanic activity was clearly worth looking at" (Taba 1994).

As Lamb was aware, there had already been a considerable amount of research into the topic of volcanic effects on climate by scientists in Europe and North America, but this work had been hampered by the lack of an adequate database. Lamb's unique contribution was to draw together various forms of evidence, including observational accounts of optical effects, atmospheric observations and geological data, thereby providing a surrogate radiative forcing record which could be tested against the climate data of recent centuries. Taking as his basis work by Sapper (1917, 1927) which documented historic eruptions and their emissions, Lamb extended Sapper's catalogue making use of additional information and devised the "dust veil index".

A veil was an accurate metaphor for the volcanic pollution. An explosive burst of volcanic material would be injected over a fairly restricted height range and then spread far more rapidly horizontally than vertically, resulting in a thin layer of pollution shrouding a fair proportion of the planet's surface. The dust veil index was a measure of the likely effect of a particular volcanic eruption on climate, taking into account the amount of material ejected, the development and decay of the veil, and effects on the radiation balance and hence climate.

The report on the work was ready for publication by the mid-1960s. The Chairman of the British National Volcanological Research Committee, Professor L. R. Wager, reviewed the draft and suggested that the report be published by the Royal Society. Unfortunately, the Meteorological Office did not agree (for reasons which will be discussed later in this account). It was several years afterwards, when interest in the topic of volcanic effects was stimulated by an Antarctic eruption and subsequent Royal Society discussion, that the Royal Society approached Lamb to ask why the report had not been forthcoming and permission to publish was granted. Though previewed, for example, in a short piece in the *Bulletin of the British Antarctic Survey* in 1967 (Lamb 1967), the conclusions of this wide-ranging assessment of the volcanic influence on climate lay on the proverbial shelf for some five years and were not to be published until 1970. Shortly afterwards, Hubert Lamb left the Meteorological Office to found the Climatic Research Unit at the University of East Anglia where he continued to update his dust veil index (Lamb 1977).

In this article, we begin by summarising the main findings of Lamb's landmark 1970 publication and then trace its influence on subsequent understanding of volcanic effects on climate, identifying major themes over the past three decades.

The development of the dust veil index

The formulation of the dust veil index, or DVI, was based on a comprehensive review of previous observational and theoretical studies of volcanic pollution in the atmosphere and its impact on climate. This review, in itself, represented a valuable contribution to the field. The DVI amounted to a synthesis of the state of the understanding of the volcanic influence at the time of its development during the 1960s (Kelly and Sear 1982).

Lamb began his treatise by discussing the nature of volcanic pollution, identifying pulverised rock (*i.e.* dust) and sulphur compounds as the climatically active components of the volcanic veil. Reviewing the nature of volcanic eruptions, and citing the significance of explosive events and injection at height into the atmosphere, Lamb introduced Sapper's scale of eruptions compiled decades earlier (Sapper 1917, 1927). The problem with existing compilations of volcanic information, and the ongoing databank project set up by the Center for Short-Lived Phenomena under the auspices of the Smithsonian Institution in Washington DC, was that these records were not collated with climate studies in mind and it was this deficiency that Lamb set out to remedy.

One of the main sources of information regarding past eruptions is the historical archive of anecdotal observations of optical effects as the volcanic pollution interferes with the transmission of visible light. For example, 'Bishop's ring' is an unusual corona surrounding the sun. The sky near the sun is observed to be white or bluish-white and the corona may be quite brilliant. The ring is sometimes edged with pink, red, brown or orange-rose. The phenomenon was first described by the Reverend S. E. Bishop, in Honolulu, following the eruption of Krakatau in 1883. The volcanic veil may produce a blue sun or a blue moon (lending meaning, though perhaps not an origin, to the phrase "once in a blue moon"). But perhaps the most commonly observed effects are the rosy sunrises and sunsets that accompany many major explosive eruptions. At dawn and dusk, the volcanic display is marked with colours ranging from a greenish tinge near the horizon through a brilliant yellow and white to a purple patch some 20° above the horizon (see Fig. 1).

The significance of anecdotal records of optical effects is twofold. First, they can be used to identify, and to date approximately, eruptions for which no other direct evidence exists. Second, the observations themselves can be used to define, at least to a first approximation, characteristics of the veil of pollution, such as particle size and height as well as geographical extent and lifetime. Lamb concluded from his review of available observational evidence, including scientific measurements, visual and actinometric data, as well as anecdotal reports of optical effects, that dust clouds with particles of 1 to 5 µm cross-section can persist for several months but that the most widespread and persistent veils more commonly consist of particles less than 0.5 to 2 µm across and last for one to three years.

Making use of various observations and methods, Lamb then assessed the height at which the volcanic pollution is found in the atmosphere. He concluded that a single erup-

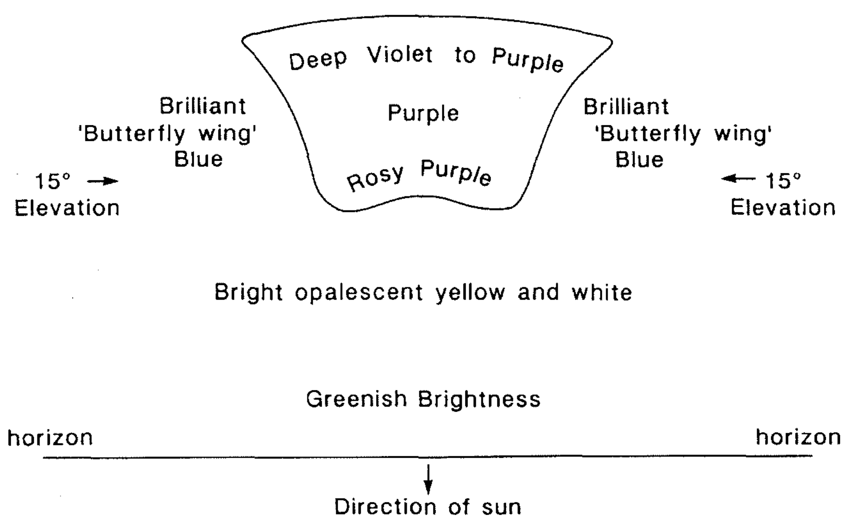

Fig. 1 Sky colours observed from Guildford (Surrey) one hour after sunset on 24 December 1963 as sketched by H. H. Lamb (from Lamb 1970)

tion may result in dust and gaseous compounds being thrown to different heights at different times and that a set of veils, each at a different height, may result. There was evidence that the veils occurred, or bunched, in particular zones: in the upper troposphere, the lower stratosphere, and at heights of 40–50 km above ground. Lamb considered those veils located in the lower stratosphere, with veil top at heights between 20 and 27 km above ground, as being the most significant as far as climate effects are concerned. Below this zone, tropospheric removal processes would limit the lifetime of any radiative impact to meteorological time-scales. Above this zone, it was unlikely that a substantial injection of pollution could occur so the veils would have a relatively minor effect on the radiation balance.

The third piece of information that contributed to the formulation of the DVI was an estimate of the lifetime of pollutants in the upper atmosphere. Lamb, adapting calculations made by Humphreys (1940), tabulated terminal velocities and stratospheric residence times for various particle diameters and then compared the results with observational evidence. He concluded that residence times of weeks to years were plausible (assuming fallout was the main removal process), with lifetimes of up to ten years perhaps possible in the polar regions where the dust might accumulate under the action of the stratospheric winds. He noted that glaciology provided the potential to generate long volcanic records through analysis of the content of stratified ice cores, a technique then in its infancy but a goal now realised (as discussed later).

The next stage was to determine the transport of the volcanic pollution from the initial point of injection. This proved the most exhaustive part of the analysis, and involved marshalling evidence from a range of sources.

Analysis of the pattern of deposition of ejected material around volcanoes reveals information about not only eruption size but also wind direction. Figure 2 shows the track of the dust cloud from an eruption of Hekla in 1947, based on surface observations of dust fallout. During this initial period after the eruption, the dust was confined to a band 100 to 140 km wide (Thorarinsson 1954). Of concern on climatic time-scales is the longer-term evolution of the dust cloud and the gradual formation of a dust veil. Lamb based his estimates of the geographical scale and lifetime of the veil resulting from eruptions at different latitudes on consideration of the characteristic circulation through the height of the atmosphere. He identified, for example, times of the year and locations where horizontal and vertical spread of material was likely to be enhanced. He then analysed available information concerning transport at different levels of the atmosphere using observations of flights of constant-height balloons and the spread of nuclear bomb test debris as well as observations of historic volcanic dust veils and aircraft sampling of pollution from modern eruptions. The importance of seasonal shifts in the atmospheric circulation when the greater influence of meridional flow patterns would accelerate the latitudinal spread of dust was noted. The net result of this analysis was the determination of weighting factors for eruptions at different latitudes dependent on the spread of the resulting veils. For example, the pollution from eruptions north of 55 to 60 °N was assumed to be largely restricted to latitudes north of 30 °N. Equatorial eruptions might have a global impact.

The final piece of information required in this assessment of the volcanic influence on climate was an estimate of the effect of the dust veils on the earth's radiation balance and hence climate. Lamb based his conclusions on observational and theoretical evidence. The effect of the volcanic pollutants on the energy balance depends on the degree of absorption and reflection, and on the impact on the incoming solar and outgoing terrestrial radiation streams. Lamb again took as his starting point work by Humphreys (1940). Humphreys had calculated, based on theory, the depletion of the direct solar beam and of the outgoing terrestrial radiation, concluding that, because of the characteristic size of volcanic dust particles, these particles were 30 times as effective in depleting the solar beam as the outgoing terrestrial radiation. Put simply, the particles are about the same size as typical solar wavelengths – so are effective reflectors of incoming radiation – but small relative to the characteristic wavelengths of the terrestrial stream – so scatter

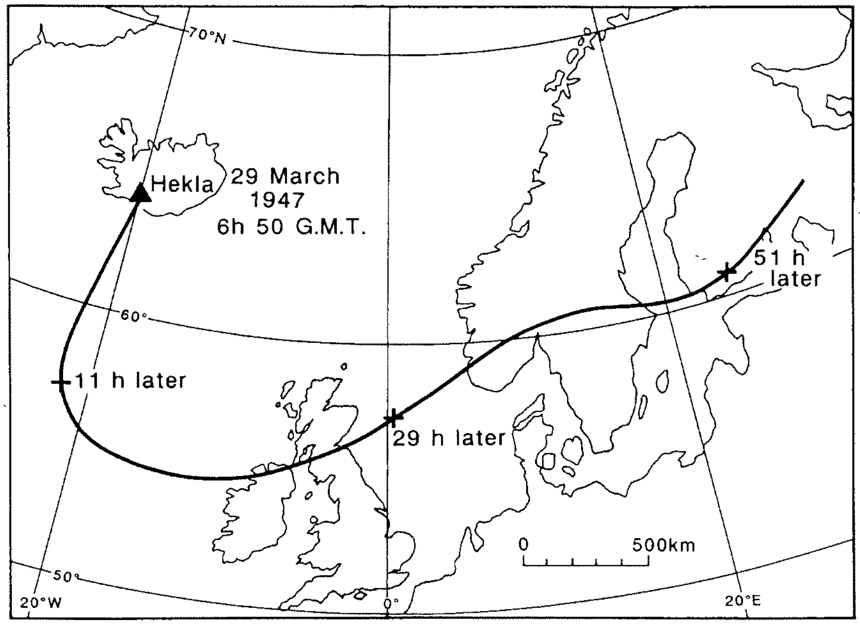

Fig. 2 Track of the dust cloud in the upper troposphere from the Hekla eruption in March 1947 (from Thorarinsson 1954)

the outgoing radiation. In fact, as Lamb noted, the volcanic veil contains a range of particle sizes and, though depletion of the incoming solar beam is likely to be the dominant effect with particles in the size range 1–2 μm most effective, it is extremely difficult to estimate from theory alone the impact of a generalised dust veil on the energy balance.

Turning to observation, Lamb first reviewed the evidence of effects on surface air temperature, confirming that depressed temperatures do appear to follow major eruptions in keeping with the theoretical arguments advanced above. He then analysed the longest records of the strength of the direct solar beam based on observations taken from mountain observatories and elsewhere (Hand 1939; Kimball 1924). Depletion of the direct solar beam was clearly evident following major eruptions. Lamb noted that the direct beam was reduced by as much as 20 per cent over the year after the eruptions of Pelée and Soufrière around the Caribbean in 1902 and the eruption of Katmai in Alaska in 1912, and for longer after the eruption of Krakatau in 1883. Reductions of a few per cent to over 10 per cent could be associated with other events. Much of the depletion of the direct solar beam would be made up by net forward scattering, for which no comparable data exist. Thus, the available radiation data, Lamb concluded, provided a guide to the significance of historic eruptions but only an indirect measure of their overall impact on the energy balance.

The DVI

Lamb formulated the DVI on the basis of the review of existing evidence summarised in the previous section. It must be appreciated that the DVI was knowingly devised as a summation of current understanding of the volcanic influence on climate, rather than as an index completely independent of climate which could be used to verify that a climate influence existed (Kelly and Sear 1982). The development of the DVI took place over a number of years, and the estimation methods were refined over time.

The first method Lamb used was based on the 'free' estimation of DVI values using information from his own compilation of material from existing catalogues of volcanic events (Gutenberg and Richter 1954; Humphreys 1940; Royal Society 1888; Sapper 1917, 1927; Shaw 1936) and subsidiary material such as the *Bulletin Volcanologique*, the *Bulletin of Volcanic Eruptions* and the *Events Cards* of the Smithsonian Institute's Center for Short-Lived Phenomena. Lamb's compilation contained information regarding the date, duration and location of volcanic events, any available estimates of dust production, including Sapper's ratings, and documentary evidence of optical effects. All this information, apart from Sapper's ratings (which were used elsewhere), was used to make subjective estimates of DVI values. To minimise the adverse effects of subjectivity, the exercise was repeated after six months and the results were reviewed again after one year. Most events were eventually reclassified using the more formal methods described below, but in cases where no firmer estimate could be made the published catalogue does include the original free estimate, with its origin clearly indicated.

The next three methods, with associated formulae, developed by Lamb can be considered as more formal representations of the physical processes underlying the volcanic effect on climate. Each formula includes parameters indicating: (i) the duration of the volcanic veil; (ii) the latitude of injection and, hence, geographical extent of the veil; and (iii) the event's potential to influence climate. The formulae are standardised to give a DVI of 1000 for Krakatau.

Once penetration of the stratosphere had been established, the lifetime of a veil, t_{mo}, was assessed on the basis of, in most cases, documentary observations of the veil and/or the duration of any related radiation and/or temperature perturbation. E_{max} is a scaling factor based on the potential climate impact of eruptions of equivalent size occurring in different latitude zones. Based on the historic evidence, E_{max} is set as 1 for eruptions occurring between 20°S and 20°N; 0.7 for events between latitudes 20 and 35°; 0.5 for events between latitudes 35 and 40–42°; and 0.3 for events in higher latitudes. The third parameter is a measure of the dust injection (note that Lamb includes sulphur gases and resulting aerosols under the generic term 'dust'). The dust injection is measured indirectly from radiation or climate data or directly through an estimate of the amount of material injected.

Formula (1) made use of radiation data, specifically the greatest percentage depletion of direct radiation following an eruption as registered by monthly averages in middle latitudes of the hemisphere of the eruption, R_{max}:

$$\text{DVI} = 0.97\, R_{max} E_{max}\, t_{mo}. \qquad (1)$$

It is assumed here that the total radiation loss was directly proportional to the direct radiation loss and that a middle-latitude estimate sufficed to represent the hemisphere.

Formula (2) made use of temperature data. T_{Dmax} is the estimated lowering of average temperature, in degrees Celsius, for the year (*i.e.* the annual average) over the middle-latitude zone of the hemisphere most affected following the eruption:

$$\text{DVI} = 52.5\, T_{Dmax} E_{max}\, t_{mo}. \qquad (2)$$

The use of temperature data here is problematic. By including temperature in this method of DVI estimation, Lamb presupposed the climatic effect and thus made the original DVI suspect for assessing the climatic impact of volcanic eruptions. In order to reduce the possibility of circular argument when using the DVI in correlations with climate data, Lamb used the temperature departure from the level prevailing immediately prior to the eruption, rather than from any long-term average. While it may not be possible to use any DVI based on temperature values alone in short-term climate studies, longer-term correlations, he considered, should not be unduly influenced. It turns out, however, that Lamb only relied on the temperature evidence for a small number of eruptions. By producing a new DVI excluding all the temperature information and using the subsequent index to force a climate model, Robock (1981a) showed that there was no significant difference compared to the result using the original DVI in the skill of the model to reproduce past climate change. The temperature information did not significantly contaminate the DVI. In part, though, it was the use of climate data in the formulation of the DVI that led to the initial reluctance of the Meteorological Office to permit publication. The swing away from empirical science and towards modelling that was under way at the time, compounded by the long-standing inability of many atmospheric scientists to take the subject of climatic change seriously, may also have contributed.

The third formula was based on estimates of the volume of material ejected, q, in terms of cubic kilometres of solid matter dispersed as dust in the atmosphere as derived from dust deposits around the volcano. Lamb considered this the least reliable of the three equations:

$$\text{DVI} = 4.4\, q\, E_{max} t_{mo}. \qquad (3)$$

Depending on the type of information available for a particular event, any or all of these equations were used and the results for each event were then averaged, sometimes with subjective correction. It is necessary to consult the full catalogue to determine the method or methods used for a particular eruption. In some cases, Sapper's rating for a historic event was the only information available and this was then used to derive a DVI on the basis of a calibration between the rating scale and the DVI using modern data. Eruptions prior to 1750 were mostly assessed on the basis of the free estimate method, volume ejected, or Sapper's ratings. Temperature data were used to assess some eruptions over the period from 1750 to the time of publication. Radiation data were only available for the period since 1883. Lamb considered the methods based on radiation and temperature data to be the most dependable, backed up by the free estimates and the volume-ejected method.

How reliable is the DVI? According to Lamb, "even when the reckoning of the dust veil index has been systematized by the use of these routine formulae, there is still a good deal of unavoidable estimation involved . . . It must simply be recognized that this is about as far as one can go towards objectivity in the assessment of past eruptions. The method seems reliable at least as an indicator of order of magnitude." Unfortunately, rather too few users of the DVI have read the full account of its derivation and, unaware of the modest value Lamb placed on its accuracy, have perhaps placed rather too much confidence in the record.

Relationship with climate

Lamb ended his treatise with a preliminary analysis of correlations between his DVI and various climate records. Relationships with temperature were only studied on decadal time-scales and longer and, for the most part, outside of the period when temperature data were the main contributor to the DVI values. Significant correlations were found between the DVI and temperature on a range of spatial scales, from central England to hemispheric. A significant correlation was also found between the volcanic record and the amount of ice on the Icelandic coasts.

Lamb considered both short- and long-term relationships between the DVI and the atmospheric circulation, making use of the long series of circulation charts for January and July that gave rise to the volcanic analysis in the first place. On the longer time-scales, a significant correlation was found between the strength of the North Atlantic westerlies and the DVI, with volcanic activity associated with a weaker circulation. There was also an indication of a relationship with the longitude of the col normally found in January over western Europe. In this case, volcanic activity was associated with a more westerly position of the col. This latter correlation may be related to the 'winter warming' effect revealed by recent analyses (Graf *et al.* 1993; Mao and Robock 1998; Robock and Mao 1992, 1995) which we will discuss later. No significant correlations were found with July circulation indicators on longer time-scales.

On the interannual time-scale, Lamb confirmed Defant's (1924) earlier observation that large volcanic eruptions were associated with a weakening of the zonal pressure gradient over the North Atlantic in the eruption year. In subsequent years, the gradient was stronger than normal. Defant attributed this strengthening to the strong cooling of the polar region during the previous year (resulting from both radiative and circulation effects) and enhancement of the equator–pole temperature gradient. Lamb stratified his analysis by eruption latitude, demonstrating that, in the case of the January indicators, Defant's findings applied for events in equatorial and northern latitudes but not for eruptions in the highest northern latitudes (which fits with the arguments presented by Defant). The relationships were less clear for the July circulation, though there was some indication of a southward shift of the pressure minimum at 0 °E after large eruptions.

Recent currents in volcanic research

The past three decades have seen a substantial investment in research on the causes of climate change, including the volcanic influence (Houghton *et al.* 1996; Kondratyev 1988). This work has resulted in improvement in the record of past volcanic activity and in better definition of the volcanic signal based on a combination of empirical analysis, theoretical argument and modelling.

Since publication of the DVI, a number of other volcanic chronologies have been compiled based on a range of different types of information (Bradley and Jones 1992; Robock and Free 1995). Mitchell (1970) produced a time-series of volcanic activity for the period 1850–1968 using data from Lamb. As discussed by Robock (1978, 1981a, 1983) and Sato *et al.* (1993), the Mitchell volcanic record for the Northern Hemisphere is more detailed than Lamb's, because Lamb excluded all volcanoes with DVI <100 in producing his Northern Hemisphere annual average DVI. Robock (1981a) used the Lamb and Mitchell indices to produce a latitudinally dependent volcanic chronology, spreading the aerosols with a simple diffusive model. A comprehensive survey of past volcanic eruptions (Simkin *et al.* 1981) has been used to produce a tabulation of the volcanic explosivity index (VEI) for all known eruptions (Newhall and Self 1982). The VEI is a geologically based measure of the power of the volcanic explosion. This index has been used in many studies as an index of the climatological impact of volcanoes without any modification – see, for example, Robock (1991) – but, as clearly pointed out by Newhall and Self (1982), it is a measure of the explosivity of eruptions, rather than stratospheric aerosol loading per se. While the VEI is positively correlated with the DVI and other more climatically relevant indices, the recent example of Mount St. Helens in 1980, with a large VEI but very small DVI, strikes the appropriate cautionary note. Keen (1983) proposed that the moon be used as a 'remote sensor' of the pollution loading of the atmosphere, using the difference between the observed brightness of a lunar eclipse and a modelled estimate for a pollution-free atmosphere.

In recent years, Sato *et al.* (1993) have produced Northern and Southern Hemisphere average volcanic indices for each month, using Mitchell's (1970) data (originally from Lamb) and other information now available. The seasonal and latitudinal distributions for the beginning of the record are uniform and offer no advantages over the DVI, but the more recent part has better resolution. Finally, Robock and Free (1995) have created a new ice core volcanic index, using only information from acid and sulphur deposits retrieved from ice cores extracted from polar regions in both hemispheres. Volcanic pollution is laid down in the annual layers of the polar ice sheets in the form of acidic snow. This process preserves a record of the atmospheric loading of volcanic sulphur and chlorine which can be observed as 'spikes' in the electrolytic conductivity of an ice core. While promising, as it is completely objective making no use of the human observer, the glaciological index has its own problems. It will, however, be improved as more ice-core measurements are taken, uncovering the signatures of past eruptions now lying buried in the ice.

In recent decades, tree-ring records have provided increasing insight into the precise dating and climatic effectiveness of large historical eruptions. Unlike ice cores, tree rings are dated with absolute accuracy and can provide a history of climate response that complements the record of atmospheric pollution loading held in the ice. Long, well replicated records representing the average growth of many trees, either from cool, moist sites or semi-arid environments, represent continuous, seasonally resolved records of changing temperatures and moisture conditions (Fritts 1976). Even at single sites, extremely anomalous ring-density or ring-width values can frequently be identified following large eruptions, indicating localised cooling (Briffa *et al.* 1990, 1995; Cleaveland 1992; Scuderi 1990).

Some tree-ring series extend back thousands of years. Characteristic wood anatomical features associated with unseasonable frosts, or simply the occurrence of much reduced growth rates in these data, have led to speculation regarding possible associations with extremely large eruptions during the pre-Christian era (Baillie and Munro 1988; LaMarche and

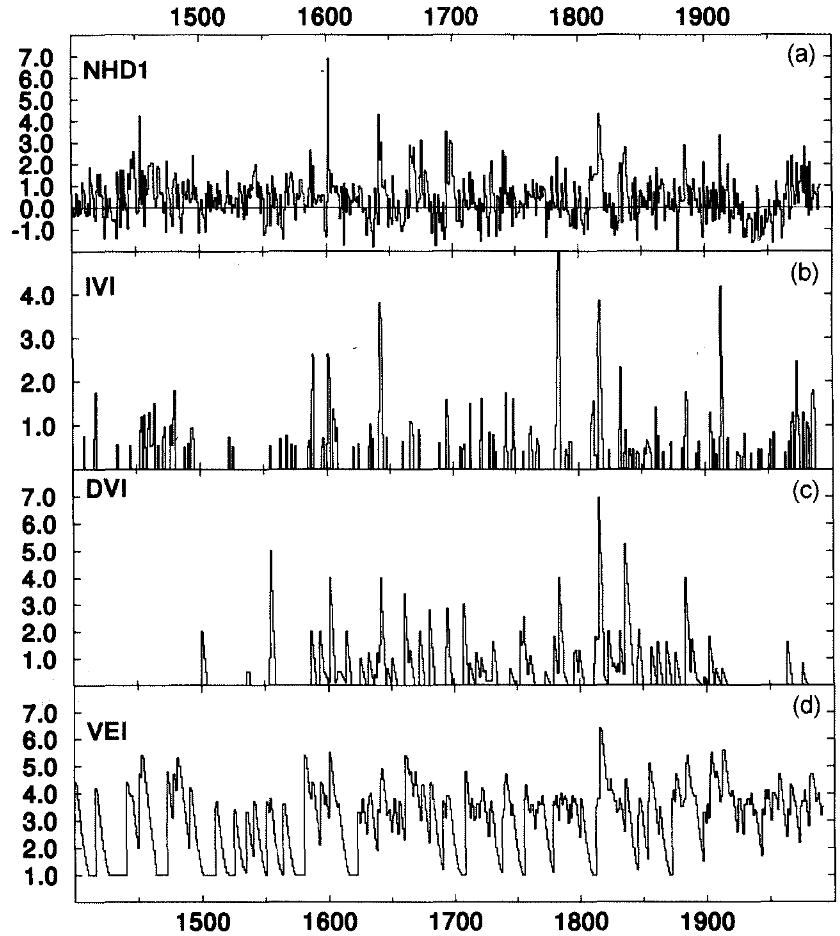

Fig. 3 A comparison of tree growth and various volcanic indices for the period 1400 to 1990. The series shown are (a) the average tree density from various Northern Hemisphere sites (NHD1 from Briffa et al. *(1998)), (b) the ice core volcanic index (IVI), (c) the dust veil index (DVI) and (d) the volcanic explosivity index (VEI) (see text for explanation). The last three have been modified according to Robock and Free (1996).*

Hirschboek 1984). The scarcity of such long chronologies and ambiguity in their precise climatic interpretation means that there must be real uncertainty in any volcanic attribution of these phenomena (Pyle 1992) and this has led to considerable controversy, such as that surrounding the tree-ring-based suggestion of a 1628 BC date for the eruption of Thera (Buckland *et al.* 1997). What is beyond doubt, though, is that the tree-ring events provide firm time markers against which other, potentially less well dated, evidence can be compared or contrasted (Baillie 1995, 1996).

Where it is possible to average data from many tree-ring chronologies with similar climate sensitivity distributed over large regions of the world, the influence of volcanic eruptions becomes glaringly apparent (Jones *et al.* 1995). A recent analysis (Briffa *et al.* 1998), in which tree-ring density records from up to nearly 400 sites spread around the northern boreal forest regions of the Northern Hemisphere were amalgamated in this way, dramatically illustrates the strong summer cooling that followed different major eruptions (Fig. 3). The cooling associated with known large eruptions such as Huaynaputina (Peru) in 1600, Tambora (Indonesia) in 1815, Krakatau (Indonesia) in 1883, and Katmai (Alaska) in 1912 can be quantified. It is also possible to confirm, or suggest, precise dates for otherwise uncertain eruptions such as Kuwae in the south-west Pacific in 1452 and

Billy Mitchell also in the south-west Pacific in either 1494 or 1586. Perhaps most significantly, the average density record strongly suggests the existence of as yet unknown eruptions such as that which probably preceded a large and abrupt cooling in 1695.

As with all the other eruption indicators, the tree-ring data can provide only part of the full picture. Seasonally restricted climate response, time-dependent changes in spatial coverage and chronology reliability, and the confounding effects of other, non-volcanic influences on tree growth all limit a direct climatic interpretation of the record, even more so a direct volcanic interpretation. Similarly, ice-derived proxies suffer from limitations such as localised geographic coverage, comparatively poor resolution and dating control, and uncertainty in interpreting the proportional origins of acidic fallout (is it indicating tropospheric or stratospheric pollution levels?). What should be clear, therefore, is that progress towards a full understanding of the past, present and probable future influence of volcanoes on climate will depend on the extent of collaboration achieved between climatologists, climate modellers and those who work with ice, tree rings and many other forms of palaeodata. Cataloguing, comparing and reconciling the various strands of evidence will be a task that is fully consistent with the strong interdisciplinary philosophy championed by Hubert Lamb.

Making use of the detailed instrumental records that have become increasingly available in recent decades, a number of authors have extended Lamb's analysis of the link between the DVI and world climate. On the shorter timescales, Kelly and Sear (1984) defined effects on Northern Hemisphere land temperatures, showing that volcanic cooling could occur within a few months of a major event. Sear *et al.* (1987) revealed a marked dependence on the hemisphere, with temperatures over the Northern Hemisphere reacting relatively swiftly to eruptions in that hemisphere but less quickly to Southern Hemisphere events. The large expanse of ocean in the Southern Hemisphere damped down the reaction of temperatures in that hemisphere, with little effect evident from northern eruptions and a slow response to Southern Hemisphere events. Bradley (1988) showed that there were seasonal differences in the impact on temperature levels, with cooling most pronounced during the summer months. Jones and Kelly (1988) compared the scale and duration of the volcanic impact on hemispheric temperature with that of the El Niño Southern Oscillation phenomenon, showing a close correspondence on both counts. In a series of papers combining empirical and modelling approaches, Robock (1978, 1979, 1981a, 1981b, 1984) demonstrated the global impact of volcanic events and stressed the importance of high-latitude feedback processes in extending the duration of the volcanic influence.

The eruption of Mount Pinatubo in the Philippines in June 1991 provided an opportunity to improve understanding of the volcano–climate link on a number of levels (see, for example, various papers in *Geophysical Research Letters*, Volume 19, 24 January 1992, reporting initial assessments of the pollution loading and possible climate impact). Direct observation of the volcanic pollutants – both particulate and gaseous – improved knowledge of their probable effect on the energy balance. Satellite information regarding the spread of the volcanic cloud and the development of a large-scale veil enabled an accurate assessment of the evolution of the climate impact. Comprehensive measurements of effects on the incoming and outgoing radiation streams provided accurate input to model estimates of the global impact and those model estimates could be tested against more reliable real-world data than had been previously available.

Stenchikov *et al.* (1998) have provided the most detailed study yet of the Pinatubo forcing. A prompt model-based forecast of the effect of the eruption on global surface air temperature (Hansen *et al.* 1992) proved accurate in timing, if somewhat exaggerated in magnitude, when compared to the observational evidence (Fig. 4), providing a good test of model performance. The eruption generated global cooling of a few tenths of a degree Celsius, most marked during the northern summer of the following year and with appreciable effects for a couple of years (Groisman 1992; Kelly *et al.* 1996; Parker *et al.* 1996; Robock and Mao 1995). Analysis of the spatial pattern of the cooling shows a widespread, coherent effect

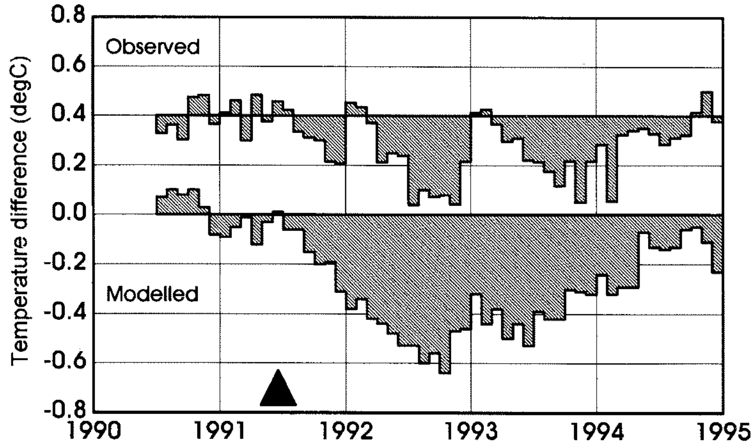

Fig. 4 Comparison of observed and forecast (modelled) global surface air temperature following the June 1991 eruption of Mount Pinatubo (indicated by the volcano symbol). Both series are departures from the 12-month average for the period from July 1990 to June 1991. For convenience, the observed record has been displaced by +0.4degC. The observed record is described in Nicholls et al. *(1996). The model forecast is from Hansen* et al. *(1992).*

over the Northern Hemisphere during the period of maximum impact (Kelly *et al.* 1996).

The occurrence of high-latitude warming during the winter months as a result of the volcanic veil has received considerable attention in recent years (Graf *et al.* 1993; Mao and Robock 1998; Robock and Mao 1992, 1995). The warming is due to the differential radiation receipt between low and high latitudes during the winter season. The volcanic aerosol layer in the tropical stratosphere is heated by the sun and the warm surface of the earth, but the effect is far less at higher latitudes. The heightened temperature contrast between equator and pole then accelerates the polar night westerly jet. This strengthened polar vortex traps the planetary waves, resulting in a tropospheric circulation pattern that advects more warm maritime air over the northern continents and causes a net warming at the surface. Evidence of the winter warming effect can be seen in the aftermath of Mount Pinatubo (Fig. 4). The cooling in the observed record is punctuated by warmer intervals during the winters of 1991/92 and 1992/93 (though no such effect is seen in this particular model simulation, it has been reproduced in other experiments).

On longer time-scales, the question of a link between decadal trends in volcanic activity and global climate has taxed investigators ever since Lamb presented his DVI. It shows a remarkable period during the 1920s to 1940s when volcanic activity was low. At the same time, the surface air temperature of the planet was rising, leading to claims that the clearance of volcanic pollution from the atmosphere was responsible for the climate trend (Robock 1978). That is not the entire explanation, though, with global warming continuing despite an upturn in volcanic activity. Recent model analyses suggest that the trend in volcanic activity plays a relatively unimportant part on these time-scales compared to, for example, the enhancement of the greenhouse effect resulting from human activity (Free 1996).

Future trends

Hubert Lamb's work on the volcanic influence on climate provides the classic example of his interdisciplinary expertise. Perhaps his major contribution to the field of climate research was as a pioneer in fusing knowledge from different disciplines, breaking ground for the next generation of scientists freed from previous constraints. It is clear, though, from the considerable amount of research stimulated by the monograph *Volcanic dust in the atmosphere* that on the basis of this publication alone Lamb would have ranked as a major contributor to current understanding of the causes of climate change. Understanding of the causes of climate change is a subject of increasing importance; to define with confidence the anthropogenic signal of global warming associated with human activity we need improved estimates of natural climate variability.

It is perhaps fitting to end this account by recording Hubert Lamb's overarching conclusions concerning the course of future climate, particularly the impact of human activity, based on his study of the natural mechanisms of climate change. Noting in his autobiography (Lamb 1997) that the climatological community has waxed and waned in enthusiasm for the subject of greenhouse warming as the record of global temperature has risen and fallen, he observed that ". . . one must feel uneasy about the confidence with which global warming has been publicised as the verdict of science in official pronouncements from various quarters." He considered that "the erratic course of the changes experienced through the twentieth century surely suggests that there are processes at work which are still not adequately understood and possibly even some influences that have not yet been identified." Nevertheless, ever aware of the need to curb society's worst excesses, he was clear that humanity must "walk humbly over the Earth. We must proceed with caution and a lively awareness of the possibilities of precipitating disaster, now that the magnitudes of our impacts on the planet has vastly increased."

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Correspondence to: Dr P. M. Kelly, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ.

The Lamb weather type catalogue

Allen Perry[1] and Julian Mayes[2]
[1]University of Wales, Swansea
[2]Roehampton Institute, London

It seems entirely possible that Hubert Lamb's daily weather type catalogue for the British Isles may prove to be one of his most lasting memorials to climatology. It is one of the most frequently cited works in the meteorological research literature and provides an unrivalled perspective on the changing behaviour of the atmospheric circulation around the British Isles. Devised in 1950, and updated in 1972, each day's weather since 1861 has been classified. Updates from 1972 were published first in *Climate Monitor* and then in *Climate News*, the newsletter of the Association of British Climatologists. A complete listing of the daily classification from 1972 to 1995 can be found in Hulme and Barrow (1997) and updates from then are on the Climatic Research Unit website (http://www.cru.uea.ac.uk). Kington (1988) has applied the scheme to the 1780s and a number of other short periods prior to 1861, including half of 1588, the stormy year of the Spanish Armada. The Lamb weather type catalogue constitutes the longest daily history of airflow patterns for any part of the world. It was in the 1940s when Lamb was working in the Forecasting Research Division of the Meteorological Office that he was instructed to prepare a classification for the Northern Hemisphere, but on learning of the preliminary work of Levick (1949, 1950) he decided to concentrate on the British Isles.

The original classification of the surface and 500 mbar daily charts was subjective, although automated objective procedures are now being used to update the catalogue. However, there are shortcomings with such procedures (Jones *et al.* 1993). In the original work Lamb took the years up to 1950 in random order to minimise the risk of any unconscious change in standards during the years spent on the exercise (Craddock and Weller 1975). The present plan is to use in the future an objective scheme to classify daily circulation patterns according to the Lamb weather typing that was developed by Jenkinson and Collison (1977). This objective scheme uses daily grid-point mean sea-level pressure data and should provide a good surrogate for the Lamb types and the essential continuity with the past.

The principles of the classification and a regional variant

Several detailed explanations of the Lamb catalogue have been published, the most recent being by Kelly *et al.* (1997) and Wheeler and Mayes (1997). Therefore, only an abbreviated description of the principles on which it is