ESPAS[1] Site Summary Series: Mauna Kea

1. Introduction

Mauna Kea (elevation 4205m, longitude 155º 28' 20" W, latitude 19º 49' 34" N) is currently one of the major ground based observatories of the planet and also has become a reference for site evaluation purposes. Unfortunately the data about actual site qualities is spread among at least as many sources as institutions in activity on the summit. This is to help clarifying the scene that the ESPAS group has undertaken the redaction of this document. The group is of course open to take into consideration all comments, inputs of concerned individuals, which should be sent to the respective topical editors indicated in the footnotes of each section.

2. Local Meteorology[2]

The high altitude of the site and its low latitude introduce some particularities in local meteorology, which are of relevance for telescope operation. Unless otherwise noted, the following data is extracted from (Kaufman and Vecchione 1981).
The wind at the summit is under 14m/s 95% of the time and under 7m/s 50% of the time. The strongest winds, blowing either from East or West, occur in January and the weakest in September. The diurnal variation is negligible. In other sites, such as La Palma (and also at Mt. Graham), the wind rose is much more uniformly distributed. This was, and still is a problem for the design of the domes (for example where to put the exhaust warm air tunnel). However, dynamical effects of the strong winds must be weighted with the low density of the air at the altitude of Mauna Kea where the typical pressure is 614mb (Bely, 1987), which corresponds to almost half of the air density than that at the sea level.
The relative humidity is very stable all along the year with an average of 48%, it is above 80% 13% of the total time, but only 3% of the usable time (less than 50% cloud cover, see next section). The boundary layer lies much below the summit between 2000 and 2400m above sea level (Erasmus, 1986).
The nighttime temperature is within 2±4 C, 90% of the time (Keck Report 90).
Severe weather conditions are a matter of concern for enclosure designers: because Hawaii can be hit by hurricanes (the last tropical storm occurred in 1957), the structures on the mountain use very high survival wind values (from 240km/h at Keck & Gemini- to 320km/h at CFHT. The 50 to 60cm annual precipitation takes place during a few intense summer storms at a rate of up to 6cm/hour. Winter storms can affect 8 days per year with up to 25cm snowfall or risk of ice accumulation (up to 12 cm thick on upwind surfaces) (Napier, 94).

---

[1] The ESPAS (ESO Search for Potential Astronomical Sites) Working Group was created in 1995 at the request of the ESO Council, and recomposed in 2000 in the frame of the OWL project. The terms of reference and the composition of the ESPAS WG are available at http://www.eso.org/gen-fac/pubs/astclim/espas/

[2] Topical editor: Marc Sarazin (msarazin@eso.org), ESO

3. Cloudiness, extinction, sky brightness[1]

3.1 Cloudiness

a) Yearly mean values of cloudiness

The cloud coverage of the sky above Mauna Kea is due to two different components (Bely, 1987): the high level clouds (cirrus) and the low level clouds (giving mainly fog or high humidity effects). They have a distinct origin and seasonal trends and their combination gives the fraction of time lost to weather at the telescopes. High clouds slightly dominate the fraction of time lost and their double peak of occurrence (in April and in October, Erasmus 1986) shows the effect in the total available fraction of nights.

One of the first detailed report on the meteorological conditions at the summit of Mauna Kea is that of McKnight and Jefferies (1968). Their data cover 16 months from 1965 to 1966. A longer record is from Morrison et al. (1973) which reports the conditions from 1965 to 1969. The detailed report by Merrill and Forbes (1987) covers, instead the period 1984-1985. Bely (1987) published the analysis from data collected at UH 2.2 m telescope from 1981 to 1985. Finally, one of the most extensive database is provided by Kaufman and Vecchione (1981), covering 9 years from 1970 to 1978. They define a photometric night when there is no cloud cover. They conclude that the yearly average of photometric nights is 45%, with a maximum in January (67%) and a minimum in October (26%). This is consistent with McKnight and Jefferies (41%), but considerably lower than Morrison et al. (56%).

The comparison with La Silla (Sarazin, 1990, updated 2001) and Cerro Tololo (Osmer and Wood, 1984) gives a marginally higher fraction of Chilean photometric nights, 62%, while one of the best recognized sites from the point of view of the clear night fraction, Cerro Paranal, reaches 77% in the period 1983-2001 (Figure 1).

Kaufman and Vecchione (1981) define spectroscopic night as a night in which there is from 1/10 to 4/10-cloud cover. A night is classified covered when more than half of the sky is covered. Following this definition, the yearly fraction of non-covered nights (photometric plus partially covered nights) at Mauna Kea is 67% (Figure 2). This value is significantly lower than the fraction of usable nights at La Silla and Cerro Tololo (about 82%, Sarazin, 1990, 2001; Osmer and Wood, 1984). The fraction of usable nights at Paranal is still the highest (about 87%). The fraction of the usable time at La Palma can be derived from the wide time baseline logbooks of the English telescopes (ING Annual Report, 1999; Rutten, 2001): an average of 75% is deduced in an 11-year interval (1989-2000). From the plots of the logbooks it is also evident that variations up to a factor two in the fraction of the time lost year to year are not rare, while the numbers from different telescopes are quite stable (typically within 10%) indicating that this criterion is reliable

Marginally different results are derived for Mauna Kea for the fraction of the used hours from the logbook of the UKIRT in the period 1985-1996 (Puxley, 2001, Gemini web pages): 72% is the usable fraction (including photometric and partially covered nights), while the "cloudless" fraction is 45%, similar to the photometric night fraction reported Kaufman and Vecchione (1981). This evaluation, however, is quite subjective

[1] Topical editor: Sergio Ortolani (ortolani@pd.astro.it), Department of Astronomy, University of Padova, Italy

because it is not easy for an observer to visually detect cirrus in a dark night and then this number can be overestimated. Bely (1987) gives an even higher fraction of usable hours (74.1%). It should be also noticed that the fraction of time lost includes some nights (around 4-5%) affected by strong winds.

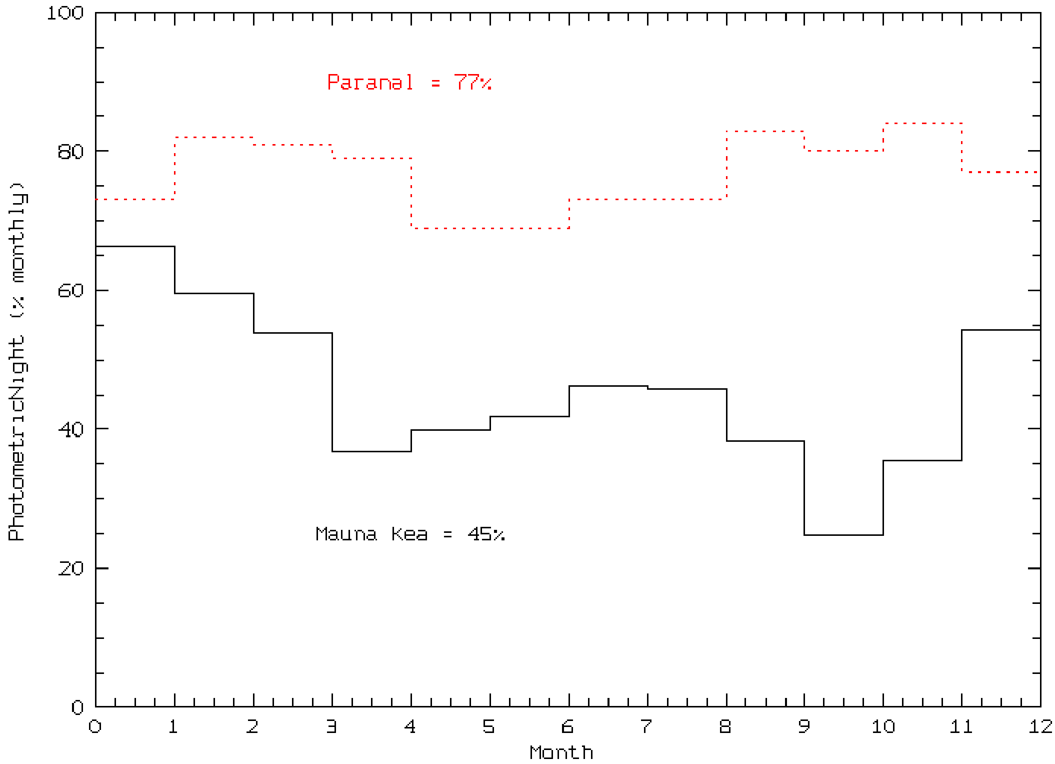


Figure 1: Monthly fraction of photometric nights averaged over a 10-year period at Mauna Kea (1970-1978, Kaufman and Vecchione (1981) and 1985, Merril (1986)) and over a 18-year period at Paranal (http://www.eso.org/gen-fac/pubs/astclim/paranal/clouds/).

b) Seasonal Trends

There is a general agreement that Mauna Kea is affected by a moderate seasonal effect, with a maximum of useful nights in February (77%) and a minimum in October (52%) and a possibly secondary minimum in April (Kaufman and Vecchione 1981). As concerning year to year variability, it is very well known that these subtropical regions are affected by high variations. Following the data published by Bely (1987) it is quite clear that the variability is mainly due to low level clouds (fog, rain, high humidity) which can vary by a factor 3 to 7, year to year. A total of a factor 2 year to year variations in the hours lost have been recorded. So far there are no detailed studies on correlation between El Niño and the local conditions on the summit, but the local ocean surface variations are limited within one Celsius degree against 3 to 4 degrees along the Pacific coast of the South America.

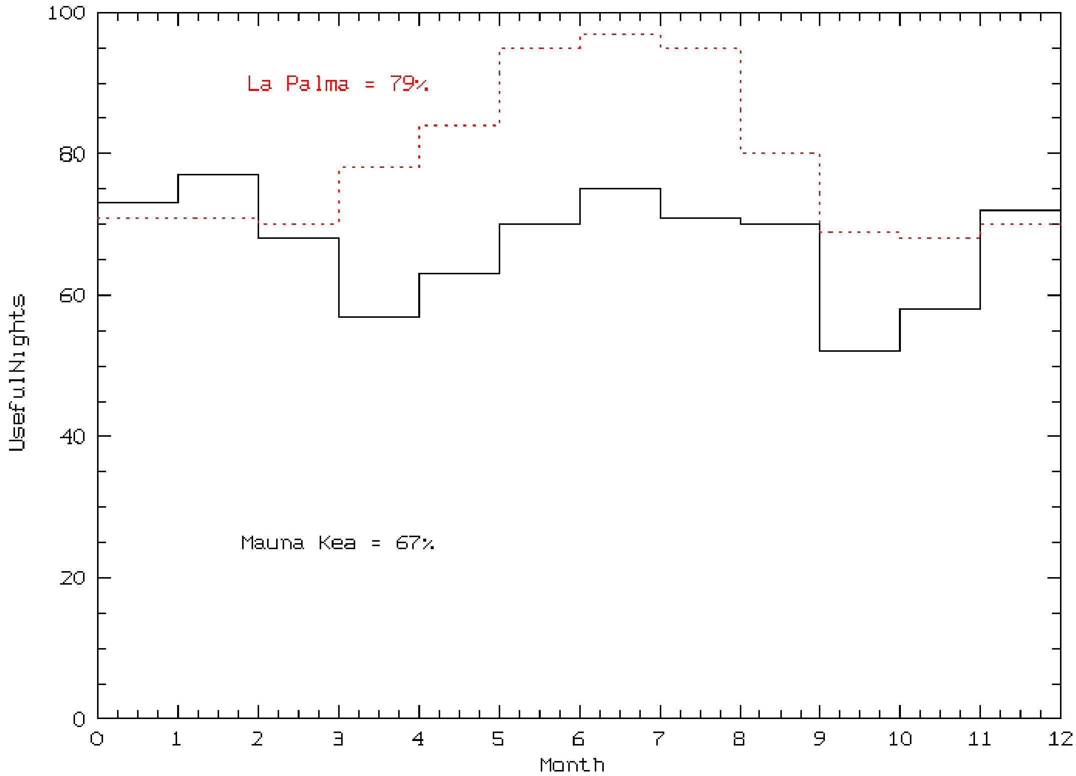


Figure 2: Monthly fraction of nights less than 50% cloudy, averaged over a 9-year period at Mauna Kea (1970-1978, Kaufman and Vecchione (1981)) and of CAMC useful nights (ie. not lost for weather) averaged over a 12-year period at La Palma (1984-1995, Buontempo (1995)).

3.2 Optical Extinction

a) Mean Values

It is generally assumed that the atmospheric optical extinction of direct light, coming from astronomical sources, is dominated by Rayleigh scattering due to small particles compared to the wavelength of the radiation (molecular diffusion), which rapidly decreases towards longer wavelengths. At long wavelengths instead the atmospheric extinction is due mainly to the extinction due to bigger particles (dust and aerosols). Finally the ultraviolet cutoff is due to the high altitude selective molecular bands of the ozone layer located at about 20 Km from the ground. For a ground astronomical site the ultraviolet cutoff is then to be expected independent of the altitude. However there are no data for the ozone layer thickness, during the night, at different geographical locations.

A detailed study of the atmospheric transmission in the optical has been published by Nitschelm (1988), which shows that the zenith transmission, at a given wavelength, in the tropical and temperate regions, is mainly a function of the altitude in the whole optical spectral range. Nitschelm provided the transmission curves at Mauna Kea (in winter and in summer) from 0.3 to 1.25 microns, at different airmasses. They clearly show the better transparency, at all the wavelengths, from Mauna Kea site compared to other developed astronomical sites. The gain is remarkable near the short wavelength cutoff: at 3.500 A the transmittance above Mauna Kea, given by Nitschelm, is 0.66 (34% absorption) while above lower sites such as La Silla and Mount Hopkins (2.400 - 2.600 m), the correspondent value is foreseen at 0.53 (47% absorption).

The measurements of the extinction from the top of Mauna Kea have been published by Krisciunas et al. (1987), based on data collected at the UH 2.2m and 0.4 m telescopes, as well as at the CFHT in the period 1980-1986 when the atmosphere was not yet affected by the volcanic eruption of the Pinatubo (Burki et al., 1995). The average mean extinction per airmass is Av=0.11 and Ab=0.19 mag., corresponding to the expected theoretical values for this altitude (Nitschelm, 1988). The equivalent values at La Silla are around Av=0.16 and Ab=0.25.

b) The UV extinction

The UV region between 3000 and 3800 A is of special astrophysical interest because there are important emission lines. Furthermore in this range we have the U standard Johnson band, which is centered around 3600 A with a 500 A width (Bessell, 1990), and the Gunn u band (Thuan and Gunn, 1976), centered at 3530 A and 400 A wide. The atmospheric absorption in this region is dominated by the ozone at the short wavelength cutoff (between 3000 and 3100 A), and by Rayleigh scatter at longer wavelengths. In a detailed analysis of the UV transmission from 3080 to 3820 A, Boulade et al. (2002) show that Mauna Kea UV transmission is better than at lower sites such as La Palma, Kitt Peak, Tololo and La Silla, in the whole range, and in particular from 15 to 20% higher at the edge of the short wavelength side of the transmission window (3100-3300 A). The authors conclude that the better transparency at Mauna Kea should be due to the higher altitude, which implies a lower Rayleigh scattering component.

The recent stratospheric ozone maps available from the satellites (available on line at ftp://jwocky.gsfc.nasa.gov/pub/eptoms/images/global/) indicate that Hawaii are located in a geographical region were the ozone has been systematically monitored from 1978 by the Total Ozone Mapping Spectrometer (TOMS). We computed the average tropospheric ozone quantity from about 8000 TOMS data from Nimbus-7 (1978-1993), Meteor-3 (1993-1994) and Earth Probe (1994-2002) in order to check the potential UV observing conditions at Mauna Kea. At Hawaii the ozone thickness shows a well-defined seasonal trend with a sharp maximum in mid-April and a minimum in December-January, reaching the lowest values around 210-220 Dobson (100 Dobson units correspond to 1-mm ozone thickness in the standard atmosphere). The mean value is 270 ± 20 Dobson. This about is about 10% lower than the standard atmospheric ozone thickness (Figure 3). Since the crossing point of the rapidly increasing ozone absorption with the Rayleigh scattering is at about 3100 A, it seems reasonable to conclude that the 20% claimed lower opacity at 3100-3150 could be a combination of the higher altitude of Mauna Kea, compared to La Silla and La Palma, and the lower ozone thickness. This should allow also a slightly shorter (about 20 A) cutoff limit. The ozone thickness above Hawaii fluctuated, from 1978 until now, with annual median values ranging from about 270 to 290, however no systematic trend appears from the analysis of the data in the last 24 years.

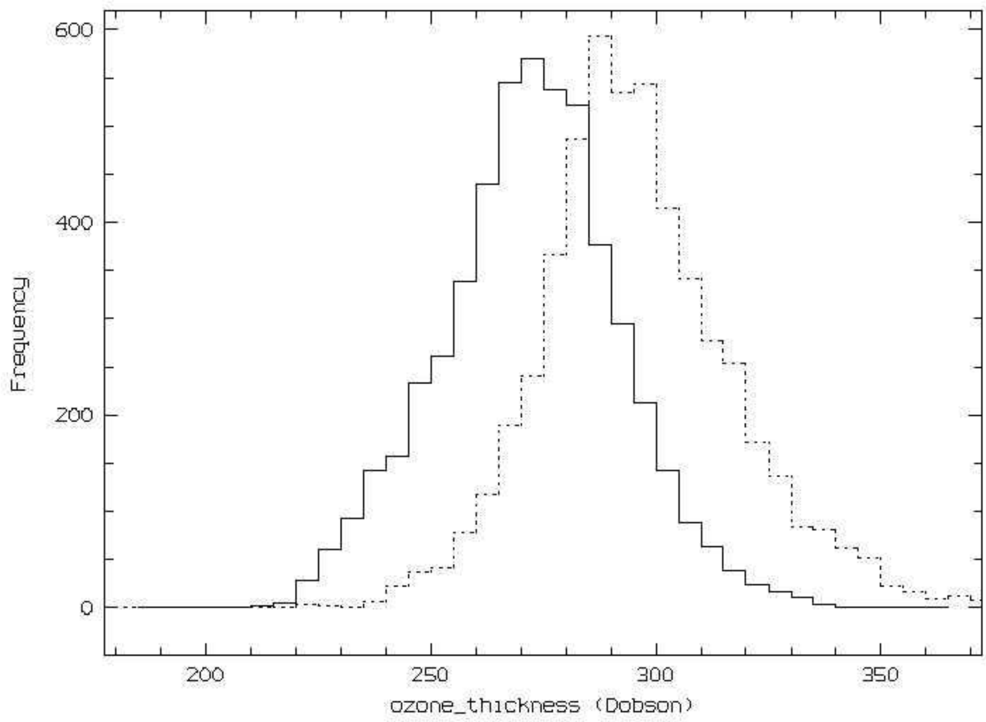


Figure 3: Distribution of the ozone thickness above Hawaii (continuum line) and Canaries (dashed line) in the period 1978-1993 from Nimbus-7 data

Acknowledgements:We acknowledge NASA/GSFC TOMS Group for the use of TOMS data. We are very grateful to Danielle Alloin for suggestions.

3.4 Visible Sky brightness

The "dark" night sky brightness in the optical, in an artificial light free site, is dominated by the zodiacal light and by the permanent aurora (airglow). The proportion of the two components strongly depends on the time during the night, year and position on the sky. The airglow has a time averaged smooth distribution on the sky, while the zodiacal light has a strong dependence on the ecliptic coordinates (mainly from the ecliptic latitude). The airglow light is modulated by the solar activity, so long term and wide sky distributed measurements should be used to determine an accurate sky brightness determination. Milky Way stars can give a contribution if the resolution of the instrument is not high enough to allow clear sky in between. It is expected that in a moonless clear night the sky brightness is equally dark in all major observatories not significantly affected by artificial lights. The sky brightness at the zenith, corrected for extinction, has been reported by Krisciunas et al. (1987, 1990): V=21.9 mag./sq.arcsec and B=22.9 at 4.200 m level, and V=21.5, B=22.3 at 2.800m level, with minima, in a complete sunspot cycle, at V=22.0 and B=23.1. These values are among the lowest in the major darkest observatories (Leinert et al., 1998). Garstang (1989), estimates an artificial light contribution at 45 degrees from zenith of about 3-4%, in 1980, due to Hilo, island of Maui, Honolulu and many other small towns in the islands, under the assumption of an average natural sky background of V = 21.99 and B = 22.99 mag/sq.arcsec. at zenith. Projections in the near future (Garstang, 1989a) are about a further 0.02 magnitudes in the next 20 years. This locates Mauna Kea as one of the darkest sites even in the next future (Garstang, 1989a, Fig. 2).

4. IR transparency, water vapour[1]

4.1 Precipitable Water Vapor

Mauna Kea has a long time been the driest site for infrared to millimeter astronomy, until observations started in Antarctica and on the high Atacama plateau in Chile. According to the data of Figure 4, with a yearly all weather medians of 2.2mm H_2O, Mauna Kea is ranking 3rd behind the South Pole and the site of ALMA in Chile.
When comparing Mauna Kea to optical sites, the daytime and cloudy nights data should be removed, thus considerably improving the statistics: Bely (1987) extracted a clear night yearly average of 1.2mm from radiosounding measurements above Mauna Kea, to be compared to 2.3mm measured by the Kitt Peak infrared radiometer at Paranal. The driest months are March to May with averages below 1mm, the worst are June to September with averages above 1.4mm.

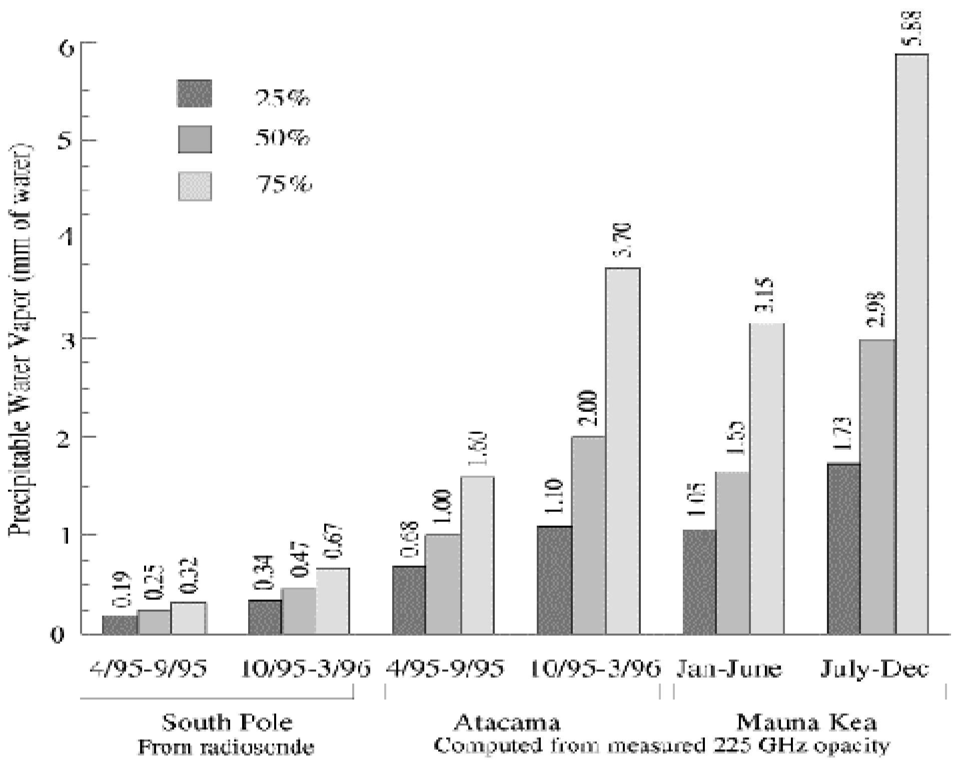


Figure 4: Respective all weather atmospheric content in precipitable water vapor at the best IR sites worldwide (Sironi, 2000).

[1] Topical editor: Sergio Ortolani (ortolani@pd.astro.it), Department of Astronomy, University of Padova, Italy

4.2 Near IR Sky brightness

The near IR sky brightness, in the J and H bands (1.2 and 1.6 microns) is dominated by the OH airglow emission lines which are very prominent between 1.5 and 3 microns. Since the OH lines are recombination molecular lines, they considerably vary during the night and also night to night. Zurita (2002) reports variations up to 150% in the integrated sky brightness from WHT records.

The Ks and the K bands (2.1 and 2.2 microns respectively) are instead strongly influenced by the thermal emission both from the atmosphere and from the instrumentation.

It is very difficult to get the K sky brightness cleaned from instrumental effects. It is quite clear, however, that the temperature plays an important role, giving lower emission in the coolest sites (an increase of about 0.1 mag./degree is estimated). It is also obvious to expect a seasonal trend with higher brightness in summer time.

The South Pole winter sky, due to the very low temperatures, is considered the darkest tested ground site in the K band.

The sky brightness in the IR bands JHK at Mauna Kea has been reported by Leggett in the UKIRT WEB pages (2000): J=15.7, H=13.6, K=13.0.

At Paranal we have J=16.5, H=14.4 Ks=13.0 (Cuby et al., 2000), while at La Palma we have J=15-16 H=13.4-14.7 and K=12.5-13.0 Ks=13.1-13.6 from NICS at TNG (Oliva, 2002), and J=16.1 H=14.7 K=12.5 Ks=12.5 from INGRID at WHT (Zurita, 2002). The comparison between TNG and WHT at La Palma is interesting because the difference of the values give an idea of the uncertainty in the numbers.

As expected, Mauna Kea appears a marginally better site in K when compared to the others, due to its higher altitude (lower temperatures), but the South Pole, in the winter nights, is obviously remarkably darker. Phillips et al. (1999) report J=16.8-16.0, H=15.2-14.2, K=15.8-14.9, Ks=15.6 mag./sq.arcsec.

An interesting result pointed out by Cuby et al. (2000) is that, in the H band, the continuum moonless sky background between the OH lines at 1.661 and 1.669 microns, at Paranal is 2.300 phot/s/sq.arcsec (corresponding to mag. 16.5), while at Mauna Kea it is about 4 times less (590 phot/s/sq.arcsec, corresponding to mag. 18.0, Maihara et al. 1993). If confirmed the very low H band continuum at Mauna Kea makes this site ideal in some fields of the infrared spectroscopy.

5. High Altitude Wind Flow[1]

It has been shown (Sarazin & Tokovinin, 2001) that the suitability of a site for adaptive optics was related to the low speed of upper atmospheric motion. We use here the NOAA Global Gridded Upper Air Statistics (V1.1, 1980-1995) to determine the monthly average velocity at the 200mb pressure level (about 12km above sea level) at the latitude-longitude grid point of Mauna Kea and other existing observatories or potential sites of interest with a 2.5 degree grid resolution. The results presented on Figure 5 and in Table 1 show that Mauna Kea is one of the most suitable place among existing observatories for slow wavefront corrugations, in particular during the months of August to November. A site within the tropical belt (Costa Rica) has been added for reference of conditions when no jet stream is present.

Month	*Costa Rica*	*La Palma*	*Gams berg*	*Mauna Kea*	*S. P. Martir*	*Mai danak*	*Paranal*	*La Silla*
1	14.2	20.9	13.6	30.6	33.7	28,6	19.5	27.2
2	14.1	24.0	12.2	34.3	37.1	27.9	19.3	24.6
3	12.5	25.7	18.5	34.6	39.5	27.2	22.0	26.4
4	10.8	29.2	28.7	33.5	31.2	24.9	29.7	31.7
5	7.8	27.9	30.2	27.7	27.6	26.5	35.5	36.2
6	8.1	22.9	33.0	21.4	21.6	30.8	35.6	36.0
7	7.6	16.2	32.1	18.7	11.3	27.3	37.4	37.7
8	8.1	15.7	29.9	16.8	12.1	28.9	36.2	38.1
9	7.6	18.1	25.6	19.1	19.7	30.2	36.6	36.3
10	7.8	18.2	26.6	21.1	27.4	25.0	35.8	39.2
11	8.3	19.5	24.0	20.8	30.4	28.2	30.9	34.0
12	12.2	23.9	20.9	26.5	32.9	27.3	24.5	27.6
mean	9.9	22.1	24.6	25.4	27.0	27.7	30.3	32.9
rms	5.2	10.8	10.2	11.0	12.3	11.0	11.4	12.9

Table 1: Monthly average wind velocity at 200mb for the period 1980-1995 (NOAA GGUAS). The yearly rms is the arithmetic average of the 12 monthly GGUAS rms computed on the basis of 2 records per day.

Erratum: this table supersedes all published data anterior to April 2003 after an error was discovered in the processing script.

[1] Topical editor: Marc Sarazin (msarazin@eso.org), ESO

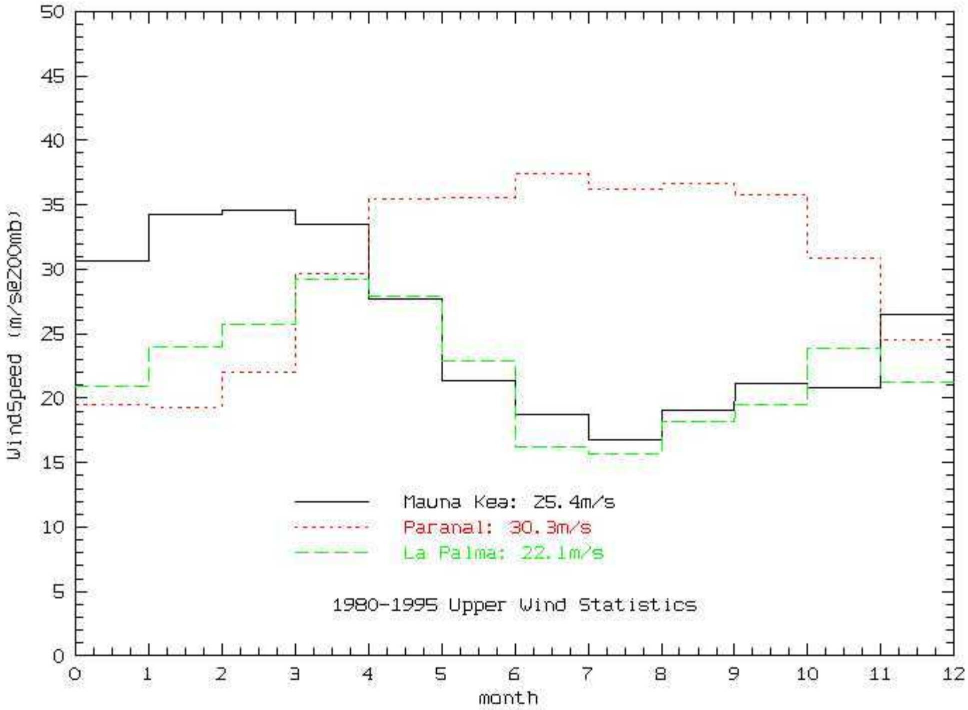


Figure 5: Monthly average wind velocity at 200mb for the period 1980-1995(NOAA GGUAS) above Mauna Kea, Paranal and La Palma observatories.

Data Source:

The Global Gridded Upper Air Statistics (GGUAS) 1980-1995 Version 1.1 is distributed by the National Climatic Data Center (NCDC). The source of the GGUAS data set was the European Centre for Medium-Range Weather Forecasts (ECMWF) 0000Z and 1200Z gridded analyses. The GGUAS data set describes the atmosphere for each month of the year represented on a 2.5-degree global grid at 15 standard pressure levels.

Coordinates	*Costa Rica*	*La Palma*	*Mauna Kea*	*Gams berg*	*S. P. Martir*	*Paranal*	*Mai danak*	*La Silla*
Lat-real		+28.76	+19.83	-23.34	+31.04	-24.63	+38.68	-29.25
Lat-closest	+10.00	+30.00	+20.00	-22.50	+30.00	-25.00	+40.00	-30.00
Long-real		-17.88	-155.47	+16.23	-115.46	-70.40	+66.90	-70.73
Long-closest	-85.00	-17.50	-155.00	+15.00	-115.00	-70.00	+65.00	-70.00

Table 2: Actual Latitude and Longitude Site coordinates used for querying the GGUAS data set with a 2.5 degree grid.

6. Seeing[1]

6.1.Telescope Image Quality

A single campaign involving SCIDAR profiler and CCD observations provides some insight into the vertical distribution of the turbulence: over one week of measurements in November 1987, the UH 88-inch telescope image quality was 0.74" FWHM at 0.5 μm and at zenith, of which 0.42" was attributed to the layers above 1km and 0.27" to the turbulence closer to the ground (Cowie, 1988). The authors argue that a perfect telescope without dome seeing would thus provide a mean image quality of 0.54", possibly better in summer. The 1984-1985 DIMM measurements by Merril and Forbes (1987) had similarly provided a value slightly below 0.6" after 30ms exposure time bias correction of their data.
A second combined SCIDAR - CCD campaign was held in June 1989 (Roddier et al., 1990). The authors concluded that the seeing is about 0.53". A more empirical approach, but based on a wider statistical sample of data, collected at the HRCam at the CFHT in 25 nights between February and June 1990, has been published by Racine et al. (1991). From 562 independent CCD measurements, after correcting the data for local and instrumental effects they obtained a median value of 0.43" +/- 0.05". They also summarized the estimates of the seeing from different sources in the period 1987-1991, deriving an average value of 0.45". These values are remarkably lower than any other developed astronomical site (La Silla, 0.86", Paranal, 0.69" (Sarazin, 1990), La Palma, 0.67" (Muñoz-Tuñon, 2001), Mt. Graham, 0.85" (Univ. of Arizona, 1987)).

The consistent discrepancy between site promises and actual telescope image quality was noted by many authors (Hall, 1989) and prompted technical improvements in most facilities aiming at decreasing locally created image degradation (dome seeing and optical aberrations)(Bely, 1987, Racine et al., 1991). The introduction of 8 to 10 meter class telescopes on the summit has drastically changed the situation because these were purposely designed for achieving the best image quality. Over 2 years of operation of Keck, for example, the median full pupil FWHM had been 0.56" and the best image 0.31", furthermore the median was reduced to 0.45" and the best to 0.24" with individual 1.2m segments (Di Vittorio, 1996).
It is thus reasonable to expect from the best locations on the summit and high enough above ground (>10m), a natural seeing at zenith and at 0.5 μm of 0.5" (Ro=20cm) possibly with ±0.1" of seasonal variations. Dedicated measurements are however needed to further refine this number which already makes of Mauna Kea the best known site for imaging quality worldwide.

6.2 Local effects

The better the site, the easier it is to degrade its quality, consequently the choice of the appropriate location of a new facility on this crowded summit has become a real challenge. Numerous authors have studied local turbulence at Mauna Kea each time a new telescope construction was planned. Most studies have predicted sizable

[1] Topical editor: Marc Sarazin (msarazin@eso.org), ESO

variations of the local seeing because of the complex local orography of this large and irregular summit.
The siting of Gemini North, was the opportunity of running a numerical model to reveal the downstream extent of the flow disturbances created by real topological features of the summit ridge (De Young and Charles, 1995).
Earlier studies have acknowledged the dependency of the thickness of the local boundary layer with wind direction and recommended sites free of obstacles to the East and the West where the wind mostly come from (Thompson, 1983). A detailed analysis of microthermal vertical profiles showed that good sites were available 200m below the summit ridge on the lava shield to the north starting from 7m above ground (Erasmus and Thompson, 1986). However, the results were later corrected and Brandt et al, 1989 came to the opposite conclusion that the north plateau site was much inferior to the cinder cone sites. These revised conclusions agree with Walker, 1983, who found significant differences between shield and NW cone, as well as a dependency on wind direction of the respective qualities of two nearby locations on the summit ridge itself (Walker, 1984).

6.3 Conclusions

The suitability of Mauna Kea for an ELT is an open question, in particular with regards to local effects which, depending on which location will be made available for construction, could turn out well below the excellent quality of the summit ridge. Plans are currently made by US teams (CELT, GSMT) to study the summit in more details. It is reasonable to assume when comparing to other sites, that the extent of local effects is directly linked to the summit size.
Also with the experience of the VLT site, we know that long term climatic trends of the atmospheric seeing are not to be excluded. Unfortunately the seeing records at Mauna Kea are too scarce even for a first guess which would require an access to year to year variations. The next section shows in particular that such high altitude areas are tightly bound to global phenomena such as global warming.
The full description of a potential or existing observatory must thus take into account local, seasonal and climatic factors. Table 3 is a first attempt to compose such a multi-scale seeing. It appears that while less sensitive to seasons, the southern hemisphere sites are severely hit by climatic trends, currently believed to be driven by the so-called Pacific Decadal Oscillation.

Zenith Seeing arcsec@0.5µm	*Yearly Median*	*Local Effects*	*Seasonal Variations*	*Climatic Trends*
Mauna Kea	0.5	+0.2 (?)	±0.1	?
La Palma [1]	0.67	±0.05 (?)	+0.10/-0.13	±0.05 (?)
Paranal	0.69	0	±0.01	±0.10
La Silla	0.86	+0.1	±0.06	±0.10

Table 3: Estimates of the absolute contribution to the yearly median seeing of seasonal, local and climatic trends at four major observatories. Reference [1]= (Muñoz-Tuñon, 2001). Numbers followed by (?) are the result of a first guess subject to revision.

7. Climatic trends at Big Island, Hawaii[1]

7.1 Introduction

The objective of this part of the report is to assess whether there have been any significant changes in climatic conditions on the Big Island of Hawaii, home to the astronomical observatory. In this context, there are two questions that arise, namely:

- Have precipitation and temperature undergone any particular shifts over the last 50 years?
- Are these changes linked to ENSO events or are they in line with trends in global climate?

The Big Island of Hawaii is located between 19°N and 20°30'N, roughly 3,300 km west of the Californian coast. In its tropical locale, it is under the prevailing influence of the Pacific High and the easterly Trade-wind systems. The storm tracks and the Pacific High follow the seasonal shift of the sun, moving north in summer and south in winter. The high thus tends to be stronger and more persistent in summer than in winter. In winter, the Trades may be interrupted for days or weeks by the invasion of fronts or migratory cyclones from the northern latitudes, and by Kona storms forming near the islands. Winter in Hawaii is thus the season of more frequent clouds and rainstorms, as well as southerly and westerly winds. An occasional hurricane can affect some of the islands, but these are rare events.

7.2 Data analysis

A 50-year data set from Mauna Loa has been used, provided on-line by the University of Hawaii climate archives (see Internet reference below); this is the closest location to the astronomical observatory and is representative of climatic processes taking place at high elevations. Based on the 50 years of monthly-mean data, temperature and precipitation records have been examined.

a) Temperature

Figure 1 shows the mean-monthly temperature recorded at the Mauna Loa site from 1955-2000. Apart from a cooling trend in the early 1970s, identified in both the year-to-year variability and in the 5-year filter (smooth line), there has been a distinct increase in annual temperatures at this site during the 50 years of record. On a century-scale, simple linear regression suggests a warming of about 3.7°C/century; this trend is statistically highly significant, with a correlation coefficient of 0.61. The arrows indicate the warm (El Niño) and cold (La Niña) phases of ENSO (El Niño/Southern Oscillation). While some of the warmer years are clearly identified with El Niño (red arrows) and colder years are related to La Niña (blue arrows), this is not systematic and certain years in the cold ENSO phase are in fact warmer than during the El Niño phase. The sequence of El Niño and La Niña years does little to halt the overall warming trend observed throughout the second half of the 20th century. A warming in excess of 3°C/century is uncommon, when compared to the global-average rise of

[1] Contribution by Paula Casals and Martin Beniston (Martin.Beniston@Unifr.CH, Topical editor), Department of Geosciences, University of Fribourg, Switzerland

0.7°C in the 20th century. This may be related to the fact that the data discussed here is from a high-elevation site; Beniston and Rebetez (1996) identified high elevations as being particularly responsive to global forcings, a finding subsequently confirmed through modeling studies by Giorgi et al. (1997).

b) Precipitation

Precipitation at Mauna Loa is a much more "noisy" variable than temperature, in terms of the interannual variability exhibited in the rainfall records in Figure 2. Much of the precipitation falls in the winter, and biases in the annual averages are essentially the result of changes in winter precipitation. The synergy with ENSO events is somewhat more apparent in this figure than for temperature, with El Niño events corresponding to above-average precipitation, and La Niña events associated with below-average precipitation. The 1983 event is particularly conspicuous here, with precipitation totals double those of the average precipitation recorded from 1955-2000. The filtered curve shows oscillations on a decadal scale that are apparently modulated by the sequence of warm and cold ENSO phases. The overall linear trend during this period is decreasing, but this trend is not statistically significant. In addition, the decreasing tendency is biased by the end of the record from 1998 onwards, during which a particularly strong and persistant La Niña has been observed.

7.3 Conclusions

It has been succinctly shown here that atmospheric warming has been particularly strong at Mauna Loa, and almost continuous since the mid-1970s; there seems to be little direct control of ENSO events on the behavior of temperature. The observed warming thus seems to be consistent – though far more amplified – with global-average warming trends. Precipitation, on the other hand, seems to be more closely linked – even if this is not systematic over the 50-year period of record –to ENSO events than to the warming tendencies. The lower-than average precipitation seen in the latter part of the 20th century, related to the latest La Niña event, is probably favorable to astronomic observations, in the sense that, intuitively, less precipitation generally implies reductions in cloud cover.

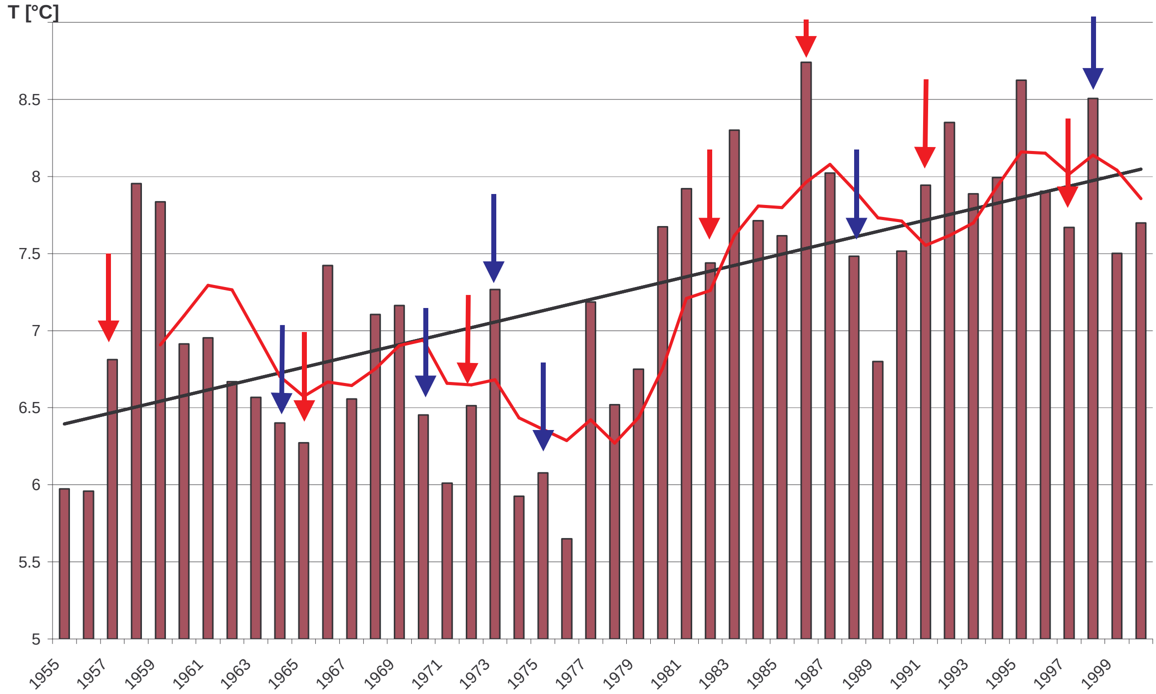


Figure 6: Annual temperatures at Mauna Loa, Big Island, Hawaii, from 1955-2000. Red arrows indicate the warm phase of ENSO, blue arrow the cold phase. The smooth red line represents a 5-year filter to remove higher-frequency fluctuations; the black line is the regression line for the period of record.

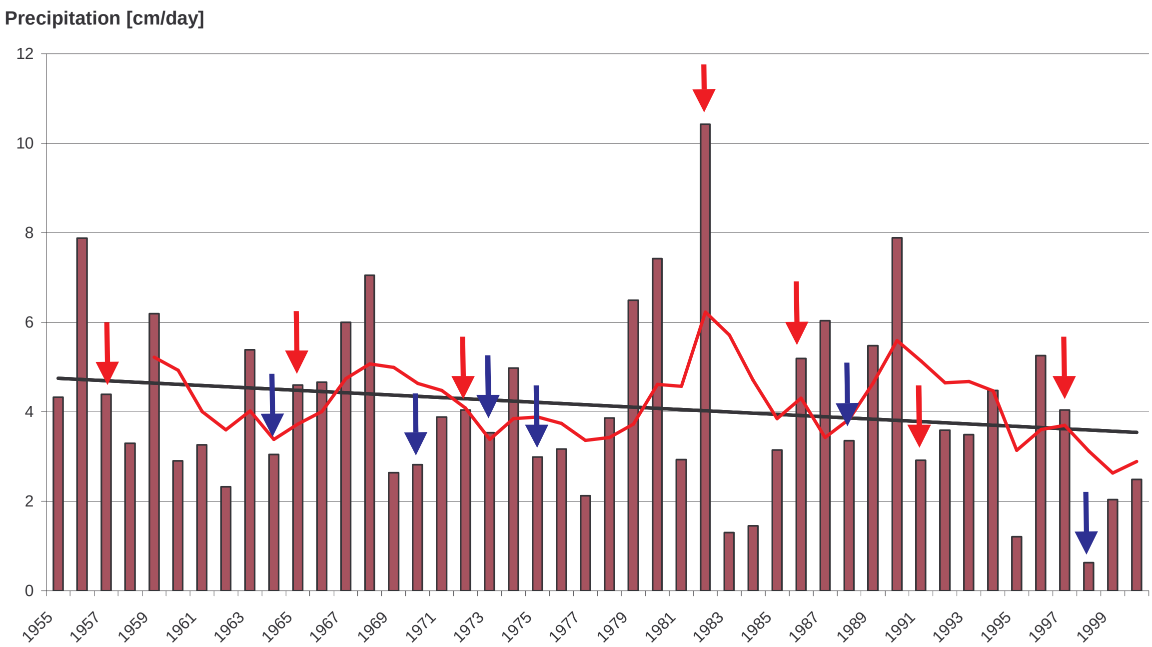


Figure 7: Annual average precipitation at Mauna Loa, Big Island, Hawaii, from 1955-2000. Red arrows indicate the warm phase of ENSO, blue arrows the cold phase. The smooth red line represents a 5-year filter to remove higher-frequency fluctuations; the black line is the regression line for the period of record.

8. Seismicity[1]

Telescopes are designed for high stiffness to maximize pointing and tracking performances under disturbances like wind buffeting. In most of the cases this results into a structural design which assures very good resistance under seismic loads, especially for telescopes of the 10m class.

In the case of ELT's, and especially in the 50m+ class, the structural design requires a substantial effort to cope with stresses caused by earthquakes, also because the order of magnitude of the eigen frequencies of the telescope structures falls into the region where the seismic response spectrum is the highest (2 to 6 Hz).

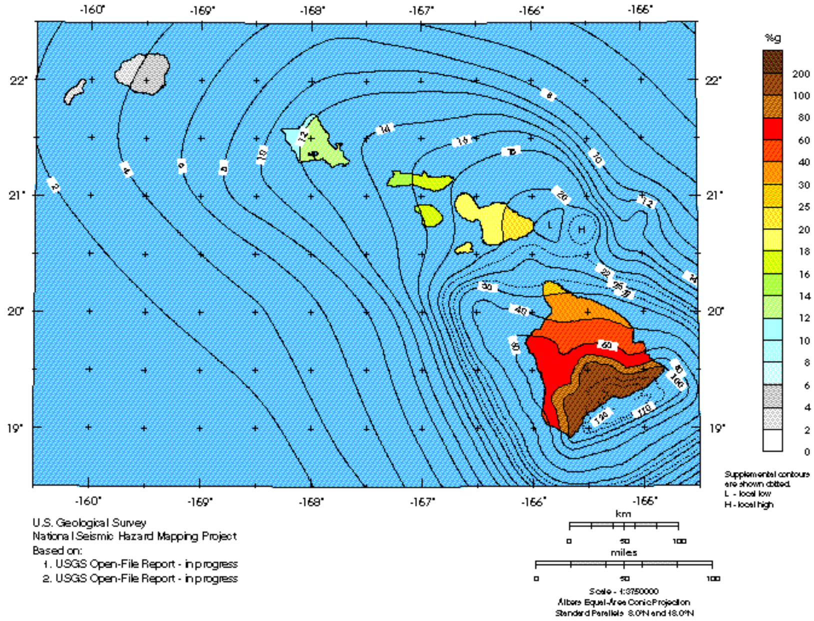
For this reason the seismic activity of a site, in terms of ground peak acceleration, is an important parameter which may decide whether an ELT can or cannot be built on that specific site. In the case of Mauna Kea the zoning of the islands in terms of ground peak acceleration shows a decreasing activity going towards the smaller islands. In the maps produced by the USGS (Figure 8), it is shown how in the Mauna Kea area the Ground acceleration with 2% and 10% probability to be exceeded in 50 years is of 0.6g and 0.4g respectively.

As shown on Table 4, these values make of Mauna Kea a site with a risk of seismic activity comparable to the one of Paranal. In particular a detailed study conducted for the Gemini project (Dames & Moore, 1994) concludes to a 10% exceedence probability in 50 years 20% higher at Mauna Kea than at Cerro Pachon, the Chilean site of Gemini South.

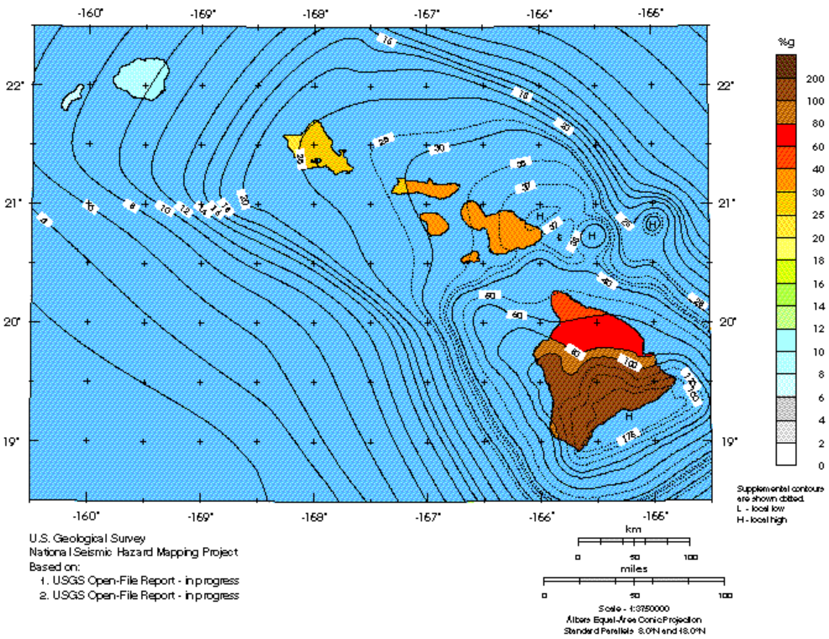
Site	*Acceleration (g)*
Mauna Kea	0.40
Paranal	0.34
La Silla	0.30
La Palma	0.06

Table 4: Peak 50-years horizontal ground peak acceleration 10% probability of exceedence in units of g

[1] Topical editor: Marco Quattri (mquattri@eso.org), ESO



Horizontal Ground Acceleration (%g)
With 10% Probability of Exceedance in 50 Years
Firm Rock - 760 m/sec shear wave velocity



Horizontal Ground Acceleration (%g)
With 2% Probability of Exceedance in 50 Years
Firm Rock - 760 m/sec shear wave velocity

Figure 8: Seismic Hazard Map for Hawaiian Islands (USGS, 2001).

9. References

-Bely, P-Y 1987, *Weather and Seeing on Mauna Kea*, PASP **99**, 560.
-Beniston, M, and Rebetez, M., 1996, *Regional behavior of minimum temperatures in Switzerland for the period 1979-1993*, Theor. and Appl. Clim. , **53**, 231 - 243.
-Bessell M.S., 1990, *UBVRI passbands*, PASP **102**, 1181.
-Boulade, O., Alloin D., Alonso M., Vigroux L., 2002, *The extinction curve and night sky properties at Mauna Kea, from 308 to 382 nm*, private communication.
-Brandt, P.N., Erasmus, A., Kusoffsky, U., Righini, A., Rodriguez, A., Engvold, O., 1989, *Results and conclusions from the meteorological phase of the LEST site survey*, LEST Technical Report **38**, Institute of Theoretical Astrophysics, Univ. of Oslo, Publisher.
-Burki, G., Rufener, F., Burnet, M., Richard, C., Blecha, A., Bratschi, P., 1995, *The Atmospheric Extinction at the ESO La Silla Observatory*, Astron. Astrophys. Suppl. **112**, 383.
-Cowie, L. and Songaila, A, *A Description of Results from the November 1987 Mauna Kea Site Campaign.*
-Cuby, J.C., Lindman, C., Moutou, C., 2000, *ISAAC: 18 Months of Paranal Science Operations*, The Messenger, **101**, 2.
-Dames & Moore Inc., 1994, *Seismic Hazard Analysis at two telescope sites, Mauna Kea, Hawaii and Cerro Pachon, Chile*, Final Report for Gemini 8m Telescope Project.
-De Young, D. S. and Charles, R. D., 1995, *Numerical Simulation of Airflow over Potential Telescope Sites*, Astron. J. **110** (6), 3107
-DiVittorio, M., *Keck Image Quality Report*, Apr. 24, 1996
-Erasmus, A.,1986, *Meteorological conditions affecting observing quality on Mauna Kea*, PASP, **98**, 254
-Erasmus, A. and Thompson, L. A., 1986, *Ground Turbulence at Mauna Kea Observatory*, Proc. SPIE **628**: 148
-Garstang, R.H., 1989, *Night-sky brightness at observatories and sites*, PASP, **101**, 306
-Garstang, R.H., 1989a, *The status and prospects for ground-based observatory sites*, Ann. Rev. Astron. Astrophys., **27**, 19
-Giorgi, F., Hurrell, J., Marinucci, M., and Beniston, M., 1997*: Height dependency of the North Atlantic Oscillation Index. Observational and model studies*. J. Clim., **10**, 288
-Hall, D. N. B., 1989, *Characteristics of Mauna Kea Relating to the Japan National Large Telescope*, Astrophysics and Space Science **160**: 243
-Hawaii data sets: http://www.wrcc.sage.dri.edu/summary/climsmhi.html
-Isaac Newton Group of Telescopes Annual Report, 1999, ed. J. Mendez, p. 31-35, Santa Cruz de La Palma, http://www.ing.iac.es/.
-Kaufman, J. M. and Vecchione, M., 1981, *A Summary of nine years of weather data from Mauna Kea Observatory*, UC TMT Report No:**66.**
-Krisciunas, K., Sinton, W., Tholen, K., Tokunaga, A., Golisch, W., Griep, D., Kaminski, C., Impey, C., Christian, C., 1987, *Atmospheric Extinction and Night-Sky Brightness at Mauna-Kea*, PASP, **99**, 887.

-Krisciunas, K., 1990. *Further measurements of extinction and sky brightness on the island of Hawaii*, PASP, **102**, 1052.
-Leggett, S., 2000, *UKIRT - IRCAM web pages*: http://www.jach.hawaii.edu/JACpublic/UKIRT/instruments/ircam/ircam3.html
-Leinert et al., (15 authors), 1998, *The 1997 reference of diffuse night sky brightness*, Astron. Astrophys. Suppl., **127**, 1.
-Maihara, T., Iwamuro, F., Yamashita, T., Hall, D.N.B., Cowie, L.I., Tokunaga, A.T., Pickles A., 1993, *Observations of the OH Airglow Emission*, PASP, **105**, 940.
-McKnight, D.R., Jefferies, J.T., 1968, *A Site Survey of Mauna Kea I. Meteorology*, internal report.
-Merril, K.M., Forbes, F.F., 1987, *Comparison Study of Astronomical Site Quality of Mount Graham and Mauna Kea*, NNTT Report n. **10**, NOAO, Tucson.
-Morrison, D., Murphy, R.E., Cruikshank, D.P., Sinton, W.M., Martin, T.Z., 1973, *Evaluation of Mauna Kea, Hawaii, as an Observatory Site*, PASP, **85**, 255.
-Muñoz-Tuñon, C., 2001, Ed., *Astronomical Quality of the Canarian Observatories (ENO)*, http://www.iac.es/eno/folleto.htm.
-Napier, P. J., 1994, *Weather Conditions at the Potential MMA Site on Mauna Kea*, ALMA Memo **113.**
-Nitschelm, C., 1988, *Theoretical transmittance in the near UV, visible and near IR through the earth atmospere*, A & A. Suppl., **74**, 67.
-Oliva, E., 2002, *TNG web pages*: http://www.tng.iac.es/instruments/nics/nics.html.
-Osmer, P.S., and Wood, H.J., 1983, *The quality of Tololo as a site*, in Site Testing for Future Large Telescopes, eds. Ardeberg and Woltjer, ESO, p. 95-102
-Phillips, A., Burton, M. G., Ashley, M. C. B., Storey, J. W. V., Lloyd, J. P., Harper, D. A., Bally, J., 1999, *The Near-Infrared Sky Emission at the South Pole in Winter*, Astrophys. J., 527, 1009.
-Racine, R., Salmon, D., Cowley, D., and Sovka, J., 1991, *Mirror, Dome and Natural Seeing at the CFHT*, PASP **103**:1020.
-Roddier, F., Cowie, L., Graves, J.E., Songalia, A., McKenna, D., Vernin, J., Azouit, M., Caccia, J.L., Limburg, E., Roddier, C., Salmon, D., Beland, S., Cowley, D., Hill, S., 1990, *Seeing at Mauna Kea: a joint UH-UN-NOAO-CFHT study*, SPIE Vol. **1236**, Advances Technology Optical Telescopes IV, 485-491.
-Rutten, R.G.M., *ING Director's Report: operations and development*, 9-10 April 2001: http://www.ast.cam.ac.uk/ING/About-ING/Strategy/ingb0105.html.
-Sarazin, M. 1990 Ed., *VLT Site Selection Working Group Final Report*, VLT Report No: **62** and updates at: http://www.eso.org/gen-fac/pubs/astclim/paranal/index.html.
-Sarazin, M., 2000, *The ideal site revisited for future ground based telescope projects*, ASP Conf. Series, **266**, 342-349.
-Sarazin ,M. and Tokovinin, A., 2001, *The statistics of isoplanatic angle and adaptive optics time constant derived from DIMM data*, Beyond Conventional Adaptive Optics, ESO Conference Proceedings, Sep. 2002, Ed. E.Vernet et al..
-Sarazin ,M., 2002, *The new tools for a global survey of potential sites for the future giant telescopes*, Proc. SPIE **2840,**291-298.
-Sironi, G, 2000, *Mm and Sub-Mm Astronomy from the Antartic Plateau*, Concordia Project Meeting, Nov. 2000, http://www-astro.unice.fr/Concordia/concord/indexConcordia.html.
-Thompson, L. A., 1983, *Mauna Kea Site Survey*, Proc. SPIE **444**: 155-160.

-USGS, 2001, *National Seismic Hazard Mapping Project*, http://geohazards.cr.usgs.gov/eq/html/his.html.
-Thuan T.X., Gunn J.E., 1976, *A new four-color intermediate band photometric system*, PASP **88**, 543.
-Walker, F. M. 1983, *A comparison of Observing Conditions on the Summit Cones and Shield of Mauna Kea*, PASP **95**, 573.
-Walker, F. M. 1984, *Re-analysis of the British NHO Site-Survey Observations at the NW Cone and 88-Inch Ridge Sites*, PASP **96**, 829.
-Zurita, A., 2002, *WHT-INGRID web pages*: http://www.ing.iac.es/Astronomy/instruments/ingrid/ingrid_throughput.html.