El Roque de Los Muchachos Site Characteristics. II. Analysis of Wind, Relative Humidity, and Air Pressure

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ABSTRACT. This paper presents an analysis of wind speed and direction, relative humidity, and air pressure taken at Telescopio Nazionale Galileo (TNG), the Carlsberg Automatic Meridian Circle (CAMC; now called Carlsberg Meridian Telescope), and the Nordic Optical Telescope (NOT) at Observatorio del Roque de Los Muchachos, in the Canary Islands. Data are also compared in order to check local variations and both long- and short-term trends of the microclimate. Furthermore, the influence of wind speed on astronomical seeing is estimated in order to better understand the influence of wide-scale parameters on local meteorological data. The analysis is done using a statistical approach. From each long series of data, we compute the hourly, daily, and monthly averages. Particular care is taken to minimize any effect due to biases in case of missing of data. Wind direction is estimated using the annual percentage of time during which winds come from fixed directions. We found that relative humidity presents a negative correlation with temperature and pressure, while pressure is correlated with temperature. The three telescopes show different prevailing wind direction, wind speed, relative humidity, and air pressure, confirming differences in local microclimate. We found that seeing deteriorates when wind speed is lower than 3.3 m s\(^{-1}\). Comparisons of wind speed and high relative humidity (\(\geq 90\%\)) shows that TNG seems to have optimal observational conditions with respect to CAMC and NOT. Air pressure analysis shows that ORM is dominated by high pressure, which indicates prevailing stable, good weather, as is to be expected from anticyclonic conditions. Finally, short-time variations of pressure anticipate temperature variations typically by 2–3 hr; this property diminishes in timescales higher than some hours and disappear in longer timescales.

1. INTRODUCTION

Since 1970, the Observatorio del Roque de Los Muchachos (ORM), located at La Palma (Canary Islands), has hosted Europe’s main astronomical telescopes. The very good astronomical conditions of the island are mainly due to a stable subsiding maritime air mass, so the telescopes are typically placed near the top of the mountain, well above the inversion layer occurring in the range between 800 and 1200 m (McInnes & Walker 1974).

All the telescopes are located along the northern edge of the Caldera de Taburiente, at the northwest side of La Palma Island, where the irregular shapes produce a complex orography, and the crowdedness of the top, due to the presence of all the astronomical observatories, suggests a possible modification of the local microclimate, making it difficult to foresee in advance the precise local meteorological parameters.

In Lombardi et al. (2006, hereafter Paper I), we have presented for the first time an analysis of temperature obtained from local meteorological towers, plus environmental conditions measured at two telescopes at ORM. Meteorological data from the Telescopio Nazionale Galileo (TNG) and the Carlsberg Meridian Telescope (formerly the Carlsberg Automatic Meridian Circle, CAMC) have been compared in order to check local variations in meteorological conditions due to temperature variations. We also investigated the influence of temperature on astronomical seeing at TNG, concluding that seeing deteriorates when the temperature around the dome at the height of the primary mirror of the telescope is at least 0.6°C higher than the temperature below that height.
The data are available in regular readings taken every 5 minutes.²

Following the same procedures as described in Paper I, we have analyzed wind speed, relative humidity, and air pressure. From each raw data series, we compute the hourly averages, and then from each set of these, we compute the monthly averages. Particular care was taken to minimize any effects due to biases in cases of missing of data, which typically occurred in wintertime. For cases of missing values, we take into account the averages obtained from two corresponding months in other years in which the values of the adjacent months are similar. A more detailed description of the adopted procedure can be found in Paper I.

Custom changes to the general analysis method for each meteorological parameter have been introduced. The following items describe these changes and include environmental information about the parameters.

1. Wind vector.—Wind vector \( \mathbf{V} \) can be assumed to be \( \mathbf{V} = w_{w} \mathbf{w}_{w}, \) where \( w_{w} \) and \( \mathbf{w}_{w} \) are wind speed and wind direction, respectively. The wind speed is measured in m s\(^{-1}\), while wind direction is in degrees (north is represented with 0°, east with 90°). The TNG sensor is placed at the top of the meteorological tower and has an accuracy of better than 2% for \( w_{w} \) and ±3° for \( \mathbf{w}_{w} \). The CAMC sensor was placed 6 m above the ground until 1991 May 16, and then it was moved to 10.5 m above the ground. It has a wind speed accuracy of ±1% below 20 m s\(^{-1}\) and ±2% above 20 m s\(^{-1}\), while wind direction is provided with a ±5° accuracy. The NOT sensor has an accuracy of better than 2% for \( w_{w} \) and better than 5° for \( \mathbf{w}_{w} \).

Wind vector has been analyzed considering its daytime and nighttime behavior. Following Paper I, daytime data have been defined in the range 10:00–16:00 (local time), while nighttime data are in the range 22:00–4:00 (local time). From each raw data series of \( w_{w} \) and \( \mathbf{w}_{w} \), we computed the hourly averages.

From each set of hourly averages of wind speed, we computed the monthly averages and then the annual averages for both daytime and nighttime.

Daytime and nighttime wind direction statistics have been evaluated by calculating the annual percentage of hours in which the wind comes from each direction \( \mathbf{D} \). The wind rose has been divided into eight mean directions (north, northeast, east, southeast, south, southwest, west, northwest), and the percentages of hours are calculated into intervals defined as \( [\mathbf{D} - 22.5°, \mathbf{D} + 22.5°] \).

2. Relative Humidity.—The relative humidity (RH) is the percentage of water vapor in the air with respect to the theoretical amount necessary to reach condensation at the same temperature.

For the three telescopes, the relative humidity sensors give an accuracy of better than 2%. The TNG sensor is placed 2 m above the ground on the meteorological tower, while the CAMC

ⁱ See http://www.ast.cam.ac.uk.

² See http://www.not.iac.es.
sensor was placed inside the dome until 1987 October 17, when it was moved to the outside north-facing wall of the dome. Finally, the NOT sensor is placed outside the dome.

Hourly, monthly, and annual averages have been calculated in the usual manner. In this case, daytime (10:00–16:00) and nighttime (22:00–4:00) statistics have also been considered, in addition to entire-day (00:00–24:00, local time) statistics.

3. Air Pressure.—Air pressure $P$ is sampled with an accuracy of $\pm 0.1$ hPa. The TNG sensor is placed 1 m above the ground on the meteorological tower, the CAMC sensor is placed inside the dome 1 m above the floor, and the NOT sensor is also placed inside the dome 2 m above the floor.

3. WIND

3.1. Wind and Astronomical Seeing

Wind speed is an important parameter, because it is linked to optical turbulence $C_n^2$ and to the wave-front coherence time (Geissler & Masciadri 2006). It is well known (Sarazin 1992) that the effects of wind velocity are negligible for $w_{\text{sp}} \in [w_{\text{min}}, w_{\text{max}}]$, where the two extremes are site dependent and $w_{\text{min}} > 0$.

In Paper I, we found that the seeing, measured as FWHMs of stellar image profiles obtained at the telescope, deteriorates when the temperature $T_w$ around the dome at the same height $h_M$ of the primary mirror of the telescope is at least $0.6^\circ$C higher than the temperature below that height (see Fig. 8 in Paper I).

We use 118 images obtained with the imaging camera OIG (Optical Imager of Galileo) at TNG, pointed near the zenith (and corrected to true zenith by a small amount) from 2000 January 31 to February 4. We computed FWHMs of several stellar images in the V-band frames. The images have been processed following the standard procedure (bias subtraction and flat-fielding) using IRAF packages. The image quality in terms of FWHM is compared to the wind speed measured at the same starting Universal Time of each image.

Figure 1 displays a comparison between $w_{\text{sp}}$ and FWHM. We see that 50% of the points are distributed below $w_{\text{sp}} < 3.3$ m s$^{-1}$ (vertical dashed line at left), with median FWHM values of 1.5″. Furthermore, for $w_{\text{sp}} \geq 3.3$ m s$^{-1}$, the distribution of the points shows a median value of 1.3″. This indicates that for $w_{\text{sp}} < 3.3$ m s$^{-1}$, the seeing deteriorates, so we can define $w_{\text{max}} = 3.3$ m s$^{-1}$. No observations are available for $w_{\text{sp}} > 12$ m s$^{-1}$ (right vertical dashed line). Sarazin (1992) shows in La Silla a limiting value of $w_{\text{max}} = 12$ m s$^{-1}$. Finally, we can...
conclude that TNG has optimal seeing conditions if \( w_{sp} \in [3.3, 12] \).

### 3.2. Wind Speed and Direction

Trade winds are the main influence on the climate of the Canary Islands. Font-Tullot (1956) affirms that the overall climate of the Canary Islands is determined by the trade winds, which have a 90% prevalence in summer and a 50% prevalence in winter, mainly coming from the northwest at the level of the observatories. Mahoney et al. (1998) point to a seasonal variation due to the Azores anticyclone, which together with the “Canary Current” drives the trade winds in a north-south direction.

Several authors have analyzed the wind pattern and speed at ORM, but the results are quite different. In the period 1971–1976, Brandt & Righini (1985) obtained a mean velocity of 6 m s\(^{-1}\) and identified a dominant wind from the northwest, with secondary peaks from northeast to southeast at ORM JOSO (Joint Organization for Solar Observations) sites. Daytime statistics compiled by Brandt & Woehl (1982) for the period 1978–1979 on the neighboring slope of ORM show a distribution in wind direction, with a prevailing component from the east.

Nighttime data taken by Mahoney et al. (1998) at the Gran Telescopio Canarias (GTC) site indicate a dominant wind from the northeast. Further analysis by Jabiri et al. (2000) at the CAMC site in the period 1987–1995 shows a prevailing wind flowing from north-northwest during the day that changes to north-northeast at night. Jabiri et al.’s wind speed analysis gives a mean \( w_{sp} \) of 2.8 m s\(^{-1}\). We can conclude that the wind direction significantly changes across the site.

In our analysis, we make use of the 7 yr databases from TNG and NOT (1998–2004) and the 20 yr database of CAMC (1985–2004). The TNG sensor is placed on the top of the meteorological tower at an altitude of 2370 m above sea level, while NOT and CAMC sensors are approximately placed at the same height of the respective dome floors, which means 2380 m for the NOT sensor and 2325 m for the CAMC sensor.

Figure 2 shows the nighttime wind roses for TNG, NOT, and CAMC, calculated by taking into account the common period 1998–2004. More detailed information about the behavior of the wind direction in each year is given in Tables 2, 3, and 4.

TNG shows a dominant northeast mode at night (see Table 2) and a less evident prevailing wind direction from south to west in the daytime. The mean wind speed is about 4.6 m s\(^{-1}\), lower than the 6 m s\(^{-1}\) found by Brandt & Righini (1985) and higher than the 2.8 m s\(^{-1}\) of Jabiri et al. (2000). The maximum wind speed measured at TNG is 26.9 m s\(^{-1}\), taken in 1999 January.

NOT has two dominant wind directions during both the nighttime (Table 3) and daytime: west and east. NOT shows a mean \( w_{sp} \) of 7.2 m s\(^{-1}\), the highest measured at ORM. The maximum wind speed measured at NOT is 29.8 m s\(^{-1}\), taken in 2004 December.

CAMC shows a lower mean wind speed (2.2 m s\(^{-1}\)). This result is also lower than the 2.8 m s\(^{-1}\) at CAMC found by Jabiri et al. (2000). The difference can be explained in terms of statistics, because our analysis uses a longer database time line. The maximum wind speed measured at CAMC is 18.3 m s\(^{-1}\), taken in 1987 April.

The wind direction for CAMC is very peculiar. Table 4 shows nighttime \( w_{dir} \) percentages per sector over the 2 decades. The northern winds seems to oscillate with a period of 10 yr, while winds from the northwest show a similar oscillation in the

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### TABLE 2

| Year | North | Northeast | East | Southeast | South | Southwest | West | Northwest |
|------|-------|-----------|------|-----------|-------|-----------|------|-----------|
| 1998 | 8.4   | 22.6      | 11.2 | 11.8      | 14.6  | 10.4      | 10.3 | 10.7      |
| 1999 | 6.0   | 20.3      | 11.3 | 8.0       | 13.8  | 12.9      | 10.3 | 17.4      |
| 2000 | 4.1   | 19.7      | 11.4 | 11.3      | 14.1  | 13.3      | 10.9 | 15.2      |
| 2001 | 6.8   | 21.5      | 14.0 | 7.0       | 12.3  | 12.5      | 12.6 | 13.3      |
| 2002 | 4.2   | 18.9      | 14.3 | 10.0      | 14.8  | 14.0      | 13.2 | 10.6      |
| 2003 | 5.0   | 17.8      | 11.3 | 9.6       | 14.7  | 15.5      | 12.8 | 13.3      |
| 2004 | 4.6   | 21.2      | 15.6 | 11.1      | 13.3  | 14.2      | 8.3  | 11.7      |

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### TABLE 3

| Year | North | Northeast | East | Southeast | South | Southwest | West | Northwest |
|------|-------|-----------|------|-----------|-------|-----------|------|-----------|
| 1998 | 1.4   | 9.6       | 15.0 | 13.8      | 9.5   | 16.1      | 18.5 | 16.1      |
| 1999 | 2.2   | 11.7      | 22.6 | 13.6      | 10.0  | 17.0      | 13.6 | 9.3       |
| 2000 | 1.8   | 9.8       | 21.9 | 16.0      | 7.9   | 13.2      | 17.6 | 11.8      |
| 2001 | 1.2   | 11.6      | 23.1 | 14.8      | 10.1  | 15.2      | 15.7 | 8.4       |
| 2002 | 3.2   | 9.0       | 20.2 | 14.5      | 7.0   | 15.4      | 19.3 | 11.4      |
| 2003 | 2.8   | 10.1      | 24.4 | 14.1      | 9.8   | 14.7      | 16.6 | 7.5       |
| 2004 | 3.9   | 8.3       | 17.1 | 13.8      | 8.0   | 16.2      | 20.6 | 12.1      |
opposite phase. Nevertheless, there is no evidence of a prevailing direction, and furthermore, the north and northwest percentages become periodically comparable to those of other directions. The situation changes dramatically in 2004, when the percentage of wind from the north increases steeply up to 71.8%. The recent behavior of the wind at CAMC point out that a deeper analysis of such phenomenon will be needed in the future.

Table 5 shows the percentage of time per sector computed for four wind speed intervals. The last bin \( \omega_{sp} \geq 15 \text{ m s}^{-1} \) is imposed as the safety observing conditions of TNG. Table 5 shows that TNG and NOT have optimal wind speed conditions about 70% of the time, compared to 16.4% at CAMC. The evaluation of total time in which \( \omega_{sp} \geq 15 \text{ m s}^{-1} \) gives an estimation of the downtime due to high wind velocity. The lost time at TNG due to \( \omega_{sp} > 15 \text{ m s}^{-1} \) is only 0.3% of the total time. CAMC never shows \( \omega_{sp} > 12 \text{ m s}^{-1} \), and NOT is more affected by high wind speed (4.2%).

### 4. RELATIVE HUMIDITY

Table 6 reports the annual averages of RH percentages for TNG, CAMC, and NOT, as well as those calculated in the winter (October–March) and summer (April–September) semesters for each year. Figure 3 shows the plot of the annual values as reported in the bottom two sections of Table 6. CAMC has the driest site, maintaining a RH \(< 58\%\) in wintertime and RH \(< 44\%\) in summertime, while both TNG and NOT have comparable trends and appear to dampen \(~15\%\) on average in wintertime and \(~7\%\) on average in summertime. The 5 yr running means of the CAMC data series show a probable change in slope after 1997. A strong anticorrelation between annual RH and temperature trends has been found. The Spearman test gives a confidence level (c.l.) \(>99\%\).

High percentages of relative humidity make observing dangerous for the instrumentation. Optical surfaces become wet and can be damaged. In their statistics, Murdin (1985) and Jabiri et al. (2000) have used a relative humidity threshold of 90%. The percentage of nights in which RH > 90% can be assumed as one of the main contributions to the total downtime of a telescope. Figure 4 shows comparisons between monthly percentages of downtime and the number of nights with RH > 90% in the period 2000–2005 for TNG and CAMC. It is interesting to note that the number of wet nights is a significant part of the total downtime, and the contribution of these nights varies with the season: it is higher in winter than in summer.

Table 7 shows the annual percentages of nights with RH > 90% for TNG, CAMC, and NOT for the period 1998–2004. NOT shows the highest percentages in each year, and TNG is only slightly lower, while CAMC has significantly lower percentages.

Our results have to be interpreted as lower limits of contributions, because the staff of each telescope can assume their

### TABLE 4
1985–2004 NIGHTTIME WIND DIRECTION PERCENTAGES FOR CAMC

| Year | North | Northeast | East | Southeast | South | Southwest | West | Northwest |
|------|-------|-----------|------|-----------|-------|-----------|------|-----------|
| 1985 | 14.2  | 11.9      | 7.6  | 8.7       | 23.2  | 5.6       | 12.6 |           |
| 1986 | 22.5  | 18.4      | 12.9 | 9.6       | 16.6  | 7.5       | 5.6  | 8.0       |
| 1987 | 7.9   | 12.8      | 13.5 | 11.3      | 14.8  | 20.1      | 12.3 | 6.6       |
| 1988 | 7.6   | 9.6       | 16.6 | 14.3      | 20.1  | 12.3      | 6.6  | 12.9      |
| 1989 | 8.6   | 10.2      | 13.0 | 12.7      | 16.7  | 17.4      | 7.8  | 13.6      |
| 1990 | 7.6   | 11.5      | 16.5 | 13.5      | 15.0  | 17.8      | 7.6  | 10.5      |
| 1991 | 8.6   | 17.6      | 16.2 | 13.1      | 13.3  | 13.4      | 6.6  | 11.7      |
| 1992 | 9.3   | 14.4      | 18.0 | 16.6      | 13.7  | 9.5       | 7.8  | 10.7      |
| 1993 | 9.7   | 13.0      | 11.8 | 14.3      | 13.8  | 10.0      | 12.7 | 14.7      |
| 1994 | 26.6  | 13.6      | 9.1  | 12.5      | 15.5  | 8.7       | 5.8  | 8.2       |
| 1995 | 24.3  | 17.9      | 6.0  | 14.9      | 11.0  | 10.0      | 7.1  | 8.8       |
| 1996 | 5.4   | 1.7       | 6.8  | 47.1      | 17.3  | 7.1       | 7.7  | 6.7       |
| 1997 | 2.6   | 5.1       | 4.7  | 11.6      | 15.9  | 16.7      | 18.2 | 25.3      |
| 1998 | 2.0   | 4.8       | 4.2  | 11.3      | 16.1  | 20.4      | 22.6 | 18.7      |
| 1999 | 2.6   | 5.1       | 4.1  | 11.1      | 16.9  | 17.4      | 20.3 | 22.6      |
| 2000 | 7.8   | 6.8       | 5.3  | 11.3      | 15.0  | 16.9      | 18.5 | 18.5      |
| 2001 | 15.4  | 15.3      | 8.2  | 11.0      | 13.7  | 16.6      | 10.9 | 9.0       |
| 2002 | 15.5  | 14.2      | 9.1  | 16.3      | 16.7  | 12.2      | 8.9  | 7.2       |
| 2003 | 16.2  | 16.7      | 8.4  | 12.4      | 12.2  | 12.5      | 11.1 | 10.5      |
| 2004 | 71.8  | 3.6       | 2.6  | 5.6       | 7.9   | 4.1       | 1.7  | 2.6       |

### TABLE 5
Nighttime Wind Statistics (1998–2004) for TNG, CAMC, and NOT

| Wind Speed Range | TNG (%) | CAMC (%) | NOT (%) |
|------------------|---------|----------|---------|
| \( \omega_{sp} < 3.3 \) | 3.3     | 83.6     | 18.5    |
| \( 3.3 \leq \omega_{sp} < 12 \) | 68.4 | 16.4     | 70.2    |
| \( 12 \leq \omega_{sp} < 15 \) | 1.1   | 0.0       | 7.1     |
| \( \omega_{sp} \geq 15 \) | 0.3  | 0.0       | 4.2     |
TABLE 6
RH PERCENTAGES FOR TNG, CAMC, AND NOT

| Year | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| **Annual** | | | | | | | | | | | | | | | | | | | | | | |
| TNG | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | |
| CAMC | 43.6 | 42.4 | 47.9 | 42.5 | 45.6 | 47.4 | 42.9 | 35.9 | 34.1 | 28.0 | 35.2 | 33.7 | 24.8 | 14.1 | 28.7 | 33.6 | 35.4 | 31.4 | 31.4 | 32.1 | 38.6 | ...
| NOT | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 39.4 | 43.7 | 37.1 | 38.6 | 44.2 | 40.9 | 50.3 | 46.3 | ...
| **Winter** | | | | | | | | | | | | | | | | | | | | | | |
| TNG | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 57.6 | 43.2 | 54.2 | 37.6 | 58.4 | 39.0 | 44.7 | 75.0 | ...
| CAMC | 40.3 | 43.8 | 48.2 | 52.2 | 49.2 | 56.5 | 57.4 | 52.7 | 47.8 | 40.4 | 40.6 | 53.1 | 44.7 | 30.9 | 12.5 | 53.0 | 33.7 | 56.4 | 36.3 | 40.8 | ...
| NOT | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 61.1 | 54.7 | 58.1 | 36.8 | 69.2 | 54.0 | 51.0 | 75.7 | ...
| **Summer** | | | | | | | | | | | | | | | | | | | | | | |
| TNG | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 26.7 | 26.2 | 28.1 | 23.6 | 30.2 | 28.0 | 43.3 | 26.6 | ...
| CAMC | 43.1 | 42.0 | 43.6 | 30.8 | 35.9 | 42.5 | 29.2 | 26.1 | 21.0 | 16.7 | 26.5 | 15.0 | 15.6 | 6.5 | 19.7 | 24.3 | 21.9 | 22.0 | 24.5 | 32.2 | ...
| NOT | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 25.4 | 21.4 | 27.5 | 23.3 | 31.2 | 25.7 | 41.1 | 20.9 | ...

The annual averages of the differences between daytime and nighttime RH (ΔRH) have been computed, and the results for the wintertime are reported in Figure 6a (top), and those for the summertime are given in Figure 6b (top). We note an oscillation of the values between 2% and 8% in the wintertime, and between 4% and 7% in the summer. Moreover, the 5 yr running means represented by the dashed lines show an increasing trend in wintertime and a steadier trend in summertime.

Figure 6a (bottom) shows wintertime annual averages of the differences between daytime and nighttime ΔT (ΔT), while those of the summertime are reported in Figure 6b (bottom). The values ΔRH and ΔT are characterized by opposite trends and own safety standard procedures concerning meteorological parameters.

In Figure 5a, daytime and nighttime trends of wintertime RH for CAMC are shown, while summertime trends are reported in Figure 5b. Figure 5 shows that RH has higher variations in wintertime than in summertime. In both cases, nighttime RH is higher compared to daytime RH. RH will simply change as a consequence of temperature changes due to the different heights of the Sun during the day. RH is higher in the first hours of the morning (the coldest part of the day) than in the afternoon (the hottest part of the day). Irregular changes of temperature and relative humidity should be due to air mass movements and the arrival of frontal systems.

The thin solid lines indicate the 5 yr running mean of the CAMC data series.
show a stronger anticorrelation in summertime (c.l. ~ 96%) than in wintertime (c.l. ~ 92%).

5. AIR PRESSURE

5.1. Long-Period Air Pressure and Weather Conditions at ORM

Table 8 reports the annual averages of $P$ for TNG, CAMC, and NOT. Since the TNG database frequently suffers missing air pressure data, we have not obtained statistically significant annual averages for the years 1998, 1999, and 2001; thus, their annual mean values do not appear in Table 8. Figure 7 shows the plot of the annual values reported in Table 8. As expected, CAMC has the highest pressures (between 773 and 776 hPa). It shows an increasing trend through the 20 yr that were sampled, while NOT shows lower values, in a range between 771 and 772 hPa. TNG annual averages display big differences compared to NOT in the years 2000 and 2002, but show very similar values in the years 2003, 2004, and 2005. Table 9 shows the maximum and minimum pressure values ever measured at the three telescopes. The difference between the absolute minimum and maximum is about 38 hPa for TNG and CAMC, and about 26 hPa for NOT. All the absolute minimums were measured in 2004 February, while the absolute maximums were registered in 2001 July.

The annual $P$ averages from CAMC show a strong correlation with temperature trends (c.l. > 99%) and an anticorrelation with the computed annual RH averages (c.l. > 99%).

The barometric correction due to the height of the three telescopes allows us to understand the differences in the mean values. We have thus investigated the exact altitude of the sensors. Caporali & Barbieri (1997) have calculated the astronomical and geodetic coordinates of TNG using a class 1 electronic theodolite and a 12 channel GPS receiver, NovAtel 3051. From this document, we know that the optical axis of TNG is located at 2378 m above sea level. The difference in height between the optical axis and the sensor is about 22 m, so we find that the TNG sensor is located at an altitude $z_{\text{TNG}} \approx 2356$ m. From topographic maps, we know that the CAMC enclosure is 2326 m above sea level, and given that the sensor is 1 m above the dome floor (see § 2), we have $z_{\text{CAMC}} \approx 2327$ m. Finally, the NOT dome is 2382 m above sea level, and the sensor is 2 m above the dome floor (see § 2), giving $z_{\text{NOT}} \approx 2384$ m.

We can compute the theoretical pressure for each site height using the barometric correction that depends on site’s scale height $H$ in the barometric law, which is dependent on the mean temperature $(T_{\text{mean}})$ of the layer in which the correction is applied. Annual temperatures for TNG and CAMC in the period 1998–2004 give a mean temperature of 9.5°C ± 0.5°C, which can be used as the mean temperature at ORM. E. Graham (2005, unpublished) gives a mean temperature of about 20.3°C.
± 0.4°C at Mazo Airport, located few meters above sea level at La Palma Island. The mean temperatures at ORM and Mazo Airport allow us to calculate the mean temperature of the layer between the sea level at La Palma and the ORM, using the weighted average of the two measurements. We obtain $\langle T_{\text{layer}} \rangle = 16.1^\circ$C ± 0.3°C.

The closest $\langle T_{\text{layer}} \rangle$ value in the standard atmospheric model from NASA’s Glenn Research Center Web site is 15°C, which gives a theoretical pressure of 763.3 hPa for an altitude of 2327 m (altitude of the CAMC sensor), which corresponds to a theoretical scale height $H_{\text{gcr}} \approx 8220$ m. If we use standard

\[ H \approx \frac{g}{\rho g c} \]

\[ \rho \approx 1.293 \times 10^{-3} \text{ kg m}^{-3} \]

\[ T \approx 288.15 \text{ K} \]

\[ g \approx 9.81 \text{ m s}^{-2} \]

\[ c \approx 297 \text{ K} \]

\[^{\text{3}}\text{ See http://www.grc.nasa.gov.}\]

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**Fig. 5.** Comparison between CAMC annual daytime (dotted line), nighttime (dashed line), and entire day (solid line) RH variations computed in (a) wintertime and (b) summertime.

**Fig. 6.** Top row: CAMC trend of differences between annual averages of daytime and nighttime RH. Bottom row: CAMC trend of differences between annual averages of daytime and nighttime $T$. The dashed lines indicate the 5 yr running means. Plots (a) are calculated in wintertime, plots (b) in summertime.
tables in Allen (2000) for $T_{\text{layer}} = 15^\circ$C, we find a theoretical scale height $H_{\text{Allen}} \approx 8430$ m. Thus, $H_{\text{CAMC}}$ and $H_{\text{Allen}}$ are in good agreement and give a mean value of $H = 8325$ m.

Once $H$ is fixed, the barometric law gives us the standard theoretical pressures scaled at the altitudes of the TNG, CAMC, and NOT sensors: $P_{\text{TNG}} = 763.3$ hPa, $P_{\text{CAMC}} = 766.0$ hPa, and $P_{\text{NOT}} = 760.8$ hPa. All these theoretical results are lower than the respective pressures in Table 8, confirming that ORM is dominated by high pressure. As expected from anticyclonic conditions, this means prevailing stable good weather.

Once the barometric correction is applied to the empirical results in Table 8, the mean pressure difference between the three telescopes is about 1 hPa. This value can be assumed to be the upper limit of the error derived from the barometric correction.

5.2. Short-Period Air Pressure and Temperature Correlations

We have also analyzed short-timescales relationships (hour to hour and day to day) between air pressure and temperature variations in wintertime (January) and summertime (July) for several years. Examples for the year 1992 at CAMC are reported in Figures 8 and 9.

For the hour-to-hour relationship, we have taken into account single-day (24 hr) trends in the hourly averages of $P$ and $T$. Figure 8 clearly shows that pressure changes anticipate changes in temperature, typically by 2–3 hr, in both the wintertime and summertime. This result can be read another way: the arrival of warmer air masses induces the collapse of pressure when temperature increases.

The relationship between $P$ and $T$ suggests that it is possible to foresee the changes in temperature 2–3 hr in advance, on the basis of the changes in air pressure. In this way, it is possible to optimize the thermalization of the telescope and the instruments, reducing the instrumental seeing. The correlation between air pressure and the temperature measured 2 hr later has a confidence level $\geq 98\%$. This correlation typically decreases if temperatures are measured 1 hr (c.l. $\geq 84\%$) or 3 hr (c.l. $\sim 95\%$) later.

Day-to-day correlations between $P$ and $T$ have also been analyzed, taking into account the daily averages for an entire month. In this case, the link between pressure and temperature becomes less evident (Fig. 9) and disappears over longer timescales. This means that the ability to make predictions based on hour-to-hour analyses vanishes on timescales higher than a few hours. A more statistical analysis should be interesting, in particular to correlate variations of pressure with the seeing, with the aim of predicting the optimal seeing conditions.

It is also interesting to note that the range between the measured maximum and minimum pressure $\Delta P$ is higher in wintertime than in summertime for both hour-to-hour and day-to-day timescales.

6. CONCLUSIONS

In this paper, we present for the first time an analysis of long-term meteorological data directly obtained from local meteorological towers at TNG, CAMC, and NOT, at a height of about 2300 m above sea level, well above the inversion layer. Wind vector $V$, split into scalar wind speed $w_{\text{sp}}$ and vectorial
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Fig. 8.—Hour-to-hour $P$ (dotted line) and $T$ (solid line) trends at CAMC for the year 1992.

Fig. 9.—Day-to-day $P$ (dotted line) and $T$ (solid line) trends at CAMC for the year 1992.

wind direction $w_{\text{dir}}$, shows a different behavior for each telescope.

We also investigated the influence of wind speed on astronomical seeing at TNG, and we found that the seeing deteriorates when $w_p < 3.3 \text{ m s}^{-1}$. Sarazin (1992) shows in La Silla a limiting value of $w_p < 2 \text{ m s}^{-1}$ and $w_{\text{max}} = 12 \text{ m s}^{-1}$. We conclude that the percentage of time in which $w_p \in [3.3, 12]$ is an indicator of good seeing conditions and shows its dependence on wind speed. TNG and NOT are in this range 70% of time, while CAMC shows only 16.4%. The evaluation of total time in which $w_p > 15 \text{ m s}^{-1}$ gives an estimation of the downtime due to high wind speed. High wind speed at TNG occurs 0.3% of the time. CAMC never shows $w_p > 12 \text{ m s}^{-1}$, while NOT is more affected by high wind speed (4.2%).

Annual averages of relative humidity (RH) for the three telescopes have been calculated for the entire year, the wintertime, and the summertime. CAMC is the driest site, while both TNG and NOT have comparable trends and appear to be damper. The 5 yr running means calculated on the CAMC data series show a probable change in slope after 1997. A strong anticorrelation between trends in RH and temperature has been found (c.l. > 99%). The percentage of nights in which RH > 90% can be assumed to be one of the main contributions to the total downtime of a telescope. NOT has the highest percentages, and TNG is only slightly lower, while CAMC has significantly lower percentages. Annual averages of the differences between daytime and nighttime RH ($\Delta$RH) in winter and in summer appear to oscillate with increasing trends anticorrelated with temperature averages $\Delta T$ taken in the same manner over the same time period. We find that $\Delta$RH and $\Delta T$ are characterized by opposite trends and show a stronger anticorrelation in summer (c.l. ~ 95%) than in winter (c.l. ~ 92%).

Air pressure is correlated with temperature (c.l. > 99%) and anticorrelated with annual relative humidity (c.l. > 99%). The analysis of annual averages of air pressure has confirmed that ORM is dominated by high pressure, which indicates prevailing stable, good weather. We have estimated the scale height of La Palma using theoretical models, finding $H = 8325$ m. Short-timescale relationships (hour-to-hour and day-to-day) between air pressure and temperature variations in the wintertime and summertime have also been analyzed. Hourly analysis shows that changes in pressure typically precede temperature changes by 2–3 hr, both in the wintertime and summertime, and this suggests the possibility of forecasting 2–3 hr in advance the changes in temperature on the basis of the changes in pressure (c.l. > 98%). In this way, it is possible to optimize the thermalization of the telescope and the instruments, reducing the instrumental seeing. This capability vanishes on timescales higher than few hours, because the link between pressure and temperature becomes less evident in the day-to-day analysis, and disappears altogether on longer timescales.

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