Nowcasting Astronomical Seeing: A Study of ESO La Silla and Paranal

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Abstract

We use extensive seeing and low-atmosphere meteorological data obtained at the European Southern Observatory's La Silla complex in Chile, and at the proposed site of the Very Large Telescope at Cerro Paranal. The differences in seeing between these two locations are studied. A prototype system is set up for predicting seeing values, given knowledge of the meteorological environment. A novel pattern recognition methodology is developed in order to do this. We assess the quality, and quantify the limitations, of such predictions. Broadly speaking, we can carry out predictions in about 80% of cases; and our good seeing nowcasts are about 70% reliable.

Key words: forecasting, prediction, nowcasting, astronomical seeing, fuzzy calculus, correspondence analysis, meteorological environment, telescope operations.

1. Background

Astronomical seeing and weather conditions are constantly monitored at the European Southern Observatory's Chilean installations. Cerro La Silla, $70^o 42' W$ $29^o 16' S$, is the current site of all ESO telescopes. Cerro Paranal, $70^o 24' W$ $24^o 37' S$, is expected to accommodate the Very Large Telescope (VLT) which is under construction.

An automated meteorological station, microthermal sensors and Differential Image Motion Monitors (DIMMs) are used to monitor the environmental conditions. Further details are discussed in Sarazin (1990) and summaries are given in a permanent series of quarterly reports (Sarazin 1992a, 1992b).

2. Motivation for Modeling and Prediction

The present study is in the context of an envisaged Astronomical Weather Station, a future interface between the observer and the terrestrial environment of the VLT observatory. Its function is to improve the quality of observations and to guarantee efficient use of telescope time. Sarazin (1991) discusses three basic functions of such a system: sensing, modeling and advising.

The VLT is a ground-based telescope, but the experience gained from the space-borne Hubble Space Telescope in such areas as remote and flexible mode observing will be availed of. The use of meteorological forecasts is very common in many domains, but curiously not in astronomy. Only recently weather satellite charts have appeared at the La Silla observatory and at the remote control center in Garching (in Munich, Germany). Although their informative power is unquestionable, they have still had little consequence on the actual observing schedule.

If we know, some time in advance, that all conditions for excellent seeing are fulfilled, then the telescope can be set in the most requiring mode and may attain excellent observing quality (0.3 arcsec at Paranal over a period of a few hours). Among broad approaches which are being investigated are: (i) physical models, based on dynamic meteorological simulations; (ii) deduction from a multivariate statistical analysis of past archived experience; and (iii) use of a monitoring station a few kilometers upwind of the observatory. The second of these is at issue in this article.

3. Remarks on Some Related Studies

Seeing is not easy to predict. Jorgenson et al. (1991; see also Jorgenson and Aitken 1992) find it to be chaotic. The framework pursued in this article attempts to relate seeing measurements to meteorological and environmental conditions *at the same time-point*. This is not quite prediction, but rather *nowcasting*. In another context, Braham (1991) concludes a comprehensive introduction to a survey with the explanation: "Indeed, the newest near-real-time weather-analysis devices for aviation have made the word 'forecasting' passé. The suggestive oxymoron in use: 'nowcasting"'.

From the statistics viewpoint, nowcasting is multiple regression, i.e. we attempt to regress a set of meteorological variables on a seeing variable. Initial experiments by us (e.g. Murtagh 1992) used a number of different methods of locally-linear and non-linear multiple regression (including the multilayer perceptron), using quantitative-valued measurements. A somewhat different tack is taken in this study, which is based on categorical-valued measurements. This was done since seeing categories ("very good", "very poor", etc.) are especially helpful for interpretation.

The method used in this article for nowcasting is *nearest neighbor regression*, where the closest historical (or archived) meteorological configuration is checked out. The corresponding seeing value is used as an estimate of the seeing (assumed unknown) associated with a given meteorological configuration. Using similar conditions which prevailed in the past is a very intuitive approach. It is also one which has been successfully used in other areas of weather-related forecasting (e.g. snow avalanche prediction in Buser et al. 1987). A slightly more enhanced approach to nearest neighbor prediction, discussed by some authors, is to note where the nearest neighbor configurations evolved to, and interpolate or extrapolate as necessary to infer a future value.

4. Data and Preliminary Treatment

A Vaisala meteorological station at La Silla was installed in February 1985. The seeing monitor was installed at nearby Cerro Vizcachas in October 1988 and moved in March 1991 close to the La Silla Schmidt telescope. Routine operation started in September 1991, with open, on-line access since January 1992. Wind direction, velocity and temperature measurements are available at 10m, 20m and 30m above ground; seeing is measured at 5m above ground; temperature, humidity and pressure are available at 2m; and ground temperature is available at -0.1m.

A Vaisala meteorological station was installed at Cerro Paranal in October 1984. Seeing measurements started in April 1987. Measurements were disrupted in July 1991 when leveling work started on the VLT site, and restarted in December 1992. Wind direction and velocity is available at 10m and 2.5m above ground; seeing at 5m; temperature, humidity and pressure at 2m; and ground temperature at -0.1m.

Variables used were the following, together with the abbreviation used in the plots and tables below:

- `s1:` Wind velocity (ms^{-1}) at 10m above ground (in certain cases of sustained missing values, windspeeds at 20m above ground were substituted).
- `s1d:` Standard deviation of the windspeed during the averaging period (20 minutes, using 2-second samples).

- `d1:` Wind direction (degrees clockwise: 0 = north, 90 = east). A clear west versus east windrose configuration is associated with Paranal, whereas La Silla has a south versus north breakdown.
- `rh:` Relative humidity (percent): the median Paranal value from end 1989 to mid 1992 was 11%, and the median La Silla value for the same period was 30%.
- `t1:` Air temperature (degrees) at 2m above ground.
- `p:` Air pressure (mB) which was investigated, but has not been used in the results quoted below.
- `see:` The seeing is measured at 5m above ground and is defined as the full-width at half-maximum of a stellar image observed with a perfect large telescope, at $0.5\mu m$ wavelength and at zenith. It is measured over periods of a few minutes throughout the night and expressed in arcseconds. One-hour averaged seeing values are used.

The following were among the initial data treatment steps undertaken. Cases (i.e. meteorological variable, and seeing, values at a given point in time) were selected so that no measurements were missing. This reduced the many tens of thousands of cases to a few thousand.

The wind direction, `d1`, at 10m was substituted for by the similar wind direction at 20m in some cases.

Air pressure, `p`, was used but found not to contribute much to the differentiation of good and bad seeing. Pressure differences were also investigated (the difference between the contemporaneous pressure, and the pressure a number of hours previously, heralding an oncoming weather front), but again found not to contribute markedly to the differentiation of good and bad seeing. Since these pressure-related variables did not help interpretation, and since their use meant that further cases were rejected since they had missing values, we dispensed with them in the analyses below.

A categorical coding of the measurements was carried out, and this will be described in the next section.

5. Fuzzy Coding and Correspondence Analysis

Each case, i.e. the seeing and meteorological variables associated with a given time point, may be represented as a point in a high-dimensional parameter space. Correspondence analysis (CA) is a dimensionality-reduction method, akin to the very widely-used principal components analysis (PCA). CA differs from the latter in that the so-called chi-squared distance is used rather than the Euclidean distance.

The issue of if, and how, to transform one's input data prior to PCA is important: this usually involves *reducing* variable vectors to unit variance, and *centering* them to zero mean. PCA then considers the observation-by-variable values as quantitative and real. Coding of input data is especially important in the case of CA, since it is best seen as a privileged method for the analysis of other types of data: qualitative or categorical, logical or binary, frequency data, mixed quantitative/qualitative, etc. Appropriately coding the input data, as in the case of input data transformations in PCA, necessarily affects the output that one will obtain.

A type of coding used in CA is to map each value of a variable onto one of a small number of categories. Consider the coding of seeing into good ("low") and bad ("high"), defined with respect to the median value. An erstwhile variable has now become two variables, with values $1, 0$ to characterize "high", and $0, 1$ to characterize "low". Note that the sum of the case's values, in the context of this recoding, is constant over all cases. This is useful in CA: it means that each case will be identically weighted, and that interpretation will not be hindered by unduly influential cases. This form of coding is termed "complete disjunctive".

The sharp division, implicit in this coding, between "high" and "low" is a little awkward in practice. For this reason, we used instead the fuzzy coding of a variable into "high", "low" and "intermediate". "High", as before, was coded $1, 0$. "Low", also as before, was coded $0, 1$. "Intermediate" was coded x, y, such that $x + y = 1$, and such that x was linearly interpolated between 1 and 0, necessitating y to be similarly linearly interpolated between 0 and 1. The division points, used to define these three categories, were the 33rd and 67th quantiles. This is a straight generalization of the complete disjunctive coding considered in the previous paragraph. It clearly also involves replacing a continuous-valued variable with a pair of variables. The latter sum to unity, so that again the sum of each case's values will be constant.

Variables `s1`, `s1d` and seeing were recoded in this way, on the basis of all La Silla cases, or of all Paranal cases. Note that this means that what was defined as good (low) or bad (high) seeing was different in these two locations. Wind direction variable `d1` was coded in the same way for Paranal, but for La Silla values were offset so that relative troughs in the distribution at 90^o and 270^o were respected: cf. comments made in the last section regarding predominant wind direction. Finally, variables `rh` and `t1` were recoded at the two sites, but with reference to seasonally-related quantile values. Table 1 summarizes variables and corresponding quantiles.

Table 1 about here

Fig. 1, Fig. 2 about here

Figs. 1 and 2 show the CA results – principal plane – for the two sites. These two-dimensional projections are optimal within the particular framework associated with the chi-squared metric. Closely located variable positions usually indicate a high degree of relationship. Illustrative relationships will be investigated in the next two sections. Any two categories relating to the same variable are related by a "law of the lever" effect: they are reflected in the origin, and their distance from the origin is related to their cardinalities. (The fuzzy generalization of cardinality will be discussed below.) The projection effect of such a planar display results in such category values not being visually equidistant from the origin. Finally, we note that the origin represents an average value. Further details of the CA method may be found, inter alia, in a brief overview in Murtagh and Heck (1987); in the comprehensive treatment of Benzécri (1992); and discussion of the fuzzy coding used is to be found in Gallego (1982).

6. Fuzzy Dependence and Relevance

The use of the correspondence analysis mapping technique in the previous section provided an impressionistic view of the associations between variables. Figs. 1 and 2 indicate a number of close associations between good seeing (`seeL`) and meteorological variables. With this as a guide, we now wish to go back to the data used, in order to pin down associations of particular interest. Such associations are often *conditional* on the presence of other variables.

It is common practice to define probabilities from observed frequencies. Our coding of variables into "high", "low", "good", or "bad" fuzzy variables, in order to enhance decision-making potential, makes this problematic. Instead, this usage of fuzzy variables leads to the use of an appropriate fuzzy calculus, rather than probability calculus (Miyamoto, 1990). Rather than (conditional) probabilities, we will consider (conditional) *possibilities*.

In the remainder of this section, we will introduce the possibility-related definitions used below. These definitions are simple analogs of the probability case.

The usual definitions of association, based on crisp values, are modified for fuzzy values. A fuzzy variable such as `rhL`, "relative humidity – Low", has a value which is a degree of "Lowness", varying between 0 and 1. Traditional, empirical probabilities, based on co-occurrence statistics, become *possibilities* in this modified framework of a fuzzy calculus. The product operator is replaced by a sum of minima, as will be seen.

Consider two arbitrary meteorological variables which we will call `A` and `B`, and good seeing, `seeL` (Fig. 3). In the crisp case, where the values of cases on these variables would be 0 or 1, the cardinality of `A` (say) is given by $\sum_i A_i$ where A_i is the value taken by case i on this variable. Again for the crisp situation, the intersection region in Fig. 3 is given by $\sum_i seeL_i A_i B_i$. Alternatively a vector notation can be used here.

Fig. 3 about here

In the fuzzy framework, where the value of case i may be 0, 1 or a value between 0 and 1, fuzzy cardinality is defined in a similar manner to the crisp case. Fuzzy intersection is defined as: $\sum_i \min(seeL_i, A_i, B_i)$. Note how this latter definition gives the crisp definition, if all variables happen to be crisp.

Conditional possibility is the name given to the generalized conditional probability. Let $\bigcap$ represent fuzzy intersection as defined above. We have:

$$poss(seeL \mid A, B) = \bigcap_i (seeL_i, A_i, B_i) / \bigcap_i (A_i, B_i)$$

$$= \sum_i (\min_i (seeL_i, A_i, B_i)) / \sum_i (\min_i (A_i, B_i))$$

This is the conditional possibility of good seeing, given `A` and `B`; i.e. the possibility of having good seeing when we are given these two meteorological variables.

To quantify associations of interest, the first measure which will be used is the foregoing: the conditional possibility of good seeing on one or more meteorological variables. This is a fuzzy success rate, given a particular environment. A second measure will be the possibility of these meteorological variables arising in practice:

$$\bigcap_i (A_i, B_i) / n$$

where n is the total number of cases considered.

7. Association of Seeing with Influential Meteorological Variables

Tables 2 and 3 display results motivated by, respectively, Figs. 1 and 2. The higher the percentages, in the case of both columns, the better. The intersection of a number of meteorological variables, hence considered together, may aid predictability of good seeing, `seeL`, but to the detriment of the second column which expresses how often these meteorological variables actually happen together.

Table 2, Table 3 about here

It may be remarked that these possibility values are very close to empirical probability values obtainable by 'crispifying' the given fuzzy values. Such possibilities have as much practical applicability as have their crisp cousins.

Both Tables 2 and 3 illustrate that taking multiple meteorological variables into account can increase the possibility of good seeing; but at the expense of the possibility of such environmental conditions actually arising. Notwithstanding the clear limitation involved here, both tables indicate that remarkably positive statements can be made in regard to good seeing.

Again we remind the reader that good seeing is defined differently for the two sites (cf. section 4); and that "possibility" is as real or as useful a figure of merit as would be be the case with empirical probabilities.

8. All Possible Unique Environmental Conditions

The categorical coding scheme used ("low", "high", and fuzzy "intermediate") easily allows enumeration of all possible combinations of environmental variables. For this, the "intermediate" category is taken as a third category.

As can be noted in Table 4, a relatively small number of unique environmental configurations were found for the cases studied.

Table 4 about here

We used such unique environmental configurations to obtain a best match relative to a given case; and to assess the best match's seeing as a prediction of the given case's seeing. This best match required an exact match of the three categories ("low", "high", and "intermediate", the latter being a constant value). Furthermore the best match environmental configuration has additional information that allows us to determine the confidence of the low seeing forecast: viz., the proportion of good seeing cases, relative to all cases, associated with the unique environmental configuration.

The plots shown in Figs. 4 and 5 tell us a lot as regards the prediction-potential of such an approach. In both figures there are two plots for each season. The first indicates how many cases were associated with the unique environmental configurations. We see that the bulk of these were low, thereby lessening the reliability of the confidence of our prediction. In fact, we imposed a threshold on the number of cases associated with unique environmental configurations: more than 4 cases (arbitrarily decided) are necessary for quantifying, with reliability, a confidence coefficient on seeing.

Fig. 4, Fig. 5 about here

The second histogram, for each season in Figs. 4 and 5, indicates how often good seeing was obtained, given a set of identical meteorological configurations. We see that there are environmental configurations such that seeing was good in all associated cases. We also note that a large number of environmental configurations have *no* associated good seeing cases. The latter cases can be used to confidently exclude good seeing.

How often can we *not* make any prediction or nowcast? This translates into the question: how many unique meteorological configurations happened very rarely, – less than or equal to (say) 4 times?

For Paranal, we find: Spring, 38.8%; Summer, 46.5%; Autumn, 43.8%; and Winter, 75.4%.

For La Silla, we find: Spring, 57.8%; Summer, 51.2%; Autumn, 55.6%; and Winter, 66.1%.

These results indicate the limits of our ability to nowcast seeing, whether good or bad, on the basis of the data used and coding adopted.

How often did more than 60% of the cases, associated with a unique meteorological configuration, indicate good seeing? Again 60% is an arbitrary cut-off. What we seek here is the number of occasions in practice that we can – with some confidence – predict good seeing.

For Paranal, we find: Spring, 12.5%; Summer, 8.9%; Autumn, 20.4%; and Winter, 32.2%.

For La Silla, we find: Spring, 16.4%; Summer, 10.2%; Autumn, 21.3%; and Winter, 36.6%.

9. Out-of-Sample Nowcasting

To empirically verify these figures, and to come closer to a production system, we tested the nowcasting ability of our system in the following way. Up to 100 cases ("up to" since some random selections were replicated) were withheld from the remaining cases, and on the basis of the latter only, the unique configurations were determined. Then, exact matches of the 100 cases were sought, among the unique configurations. If no such match was found, or if the unique combination was associated with too few cases, then we decided that no prediction was possible. The latter was relaxed to 3: more than 3 cases were required to exist for legitimate prediction based on an exact match with a unique combination.

The seeing values associated with the best match cases were used to estimate seeing. Given, however, that a certain number of good, bad and intermediate seeing values are associated with the best match cases, we must use this information to guide our choice of estimate. A *confidence* coefficient was defined as: number of instance of good seeing, among the best match cases, plus 0.5 times the number of instances of intermediate seeing, plus zero times the number of instances of bad seeing, relative to the total number of instances.

Next, to simplify the assessment of results obtained, we fuzzified this confidence coefficient: a value less than $\frac{1}{3}$ signified a high (i.e. bad) seeing estimate; a value between $\frac{1}{3}$ and $\frac{2}{3}$ inclusive signified an intermediate seeing estimate; and a value above $\frac{2}{3}$ signified a low (i.e. good) seeing estimate. Knowing the seeing value of the withheld test case then allowed a comparison. The contingency tables shown in Table 5 display the results obtained. Each contingency table is based on five runs, in each of which up to 100 cases were withheld; then estimates of seeing were obtained and compared with the known seeing.

Table 5 about here

Various measures such as hit rate and completeness (see Murtagh and Adorf 1991), or recall and precision, can be derived from these contingency tables. One can see that, for La Silla, when our system stated that good seeing was expected, then this was in fact the case in 29 cases, with 11 intermediate cases, and 3 errors (i.e. good seeing predicted, and bad seeing actually happening). This would appear quite good, and the table of Paranal results indicates a similar outcome. On the other hand, note that many actual cases of good seeing were "lost" by our system: in the case of Paranal, 41 (or, depending on usage of such data, 41 + 62) cases of misleading estimates were provided by our system.

There is always a trade-off in such systems between hit accuracy, on the one hand, and completeness, on the other. The onus is on the user to state how the system should be used: conservatively or optimistically. Should one attempt to benefit from any possible foreseeable good seeing potential, or should one attempt to avoid anything other than good seeing at all costs? Firstly and foremostly, such considerations translate into how we handle the "intermediate" category. It will be recalled that this is a neutral category, indicating intermediate values of seeing.

If we look at the reliability of our system as indicated by how many times good seeing actually happens, relative to how many times our system estimated that good seeing should happen, we find values of 64% for La Silla and 76% for Paranal (i.e., with reference to Table 5, respectively 29/(29+11+3) and 19/(19+4+2)).

Such higher predictability at La Silla points to the fact that seeing is more determined, there, by local near-ground effects. The incorporation of higher atmospheric variables would therefore, we feel, help to improve the predictability of seeing at Paranal.

10. Conclusions

We have described a system for nowcasting astronomical seeing. We have derived high-reliability estimates of predictability of seeing at two observatory sites, La Silla and Paranal. These estimates can be used as a base-line against which to measure other, future statistical modeling and forecasting methodologies.

One use of what has been achieved is to predict temperature, humidity, and the other meteorological variables at a few time steps into the future; and then to use the predicted environmental configuration to determine the seeing. We believe that such variables are more accurately predictable compared to direct prediction of seeing a number of time steps ahead.

Accurate temperature forecasts were obtained in Murtagh et al. (1992a, 1992b). 24-hour ahead predictions were carried out, based on temperatures at 0 (current time), 24 and 48 hours previously, and pressures at 0 and 24 hours previously. A nearest neighbor method was used, similar to what has been used here. Results using a multilayer perceptron approach, and results based on autoregressive modeling with exogenous inputs, were both compared with the preferred forecasting method. "Carbon-copy" prediction of temperature within half a degree centigrade of the actual temperature value was obtained in 20.5% of cases. The forecasting method employed by us found predictability within half a degree to be 62.3%. If the accuracy of prediction was relaxed to 2 degrees, then a correct temperature forecast was obtained in 85.1% of cases.

The assessment figures for nowcasting of seeing which are quoted in this article, and the system which has been prototyped, are a contribution to a future telescope decision support system.

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Variable		Paranal Quantiles 33rd	67th	50th	La Silla Quantiles 33rd	67th	50th
s1	windspeed	4.4	7.9	6.0	2.9	5.8	4.3
s1d	windspeed std. dev.	0.1	0.2	0.1	0.1	0.2	0.1
d1	wind direction (1)	90	319	159	208	233	216
rh	humidity						
	Autumn	7	13	10	15.75	26	21
	Winter	7	13	10	15.75	26	21
	Spring	5	10	7	26	36	30
	Summer	11	19	15	42	52	47
t1	temperature						
	Autumn	11.2	13	12.1	10.7	12.7	11.9
	Winter	11.2	13	12.1	10.7	12.7	11.9
	Spring	11	12.8	12	10.3	13.5	11.85
	Summer	12.4	13.6	13	12.7	14.5	13.7
see	seeing	0.56	0.74	0.64	0.77	0.98	0.87

Table 1
Seeing and meteorological variables used for analyses

Table 2
Paranal results (1989–1991)

Season	Good seeing given...	Conditional possibility of good seeing	Possibility of variable(s) happening
Autumn	`rhL`	0.614	0.506
	`rhL` and `t1H` and `d1H`	0.743	0.196
Winter	`rhH` and `d1H` and `s1L` and `s1dL` and `t1L`	0.930	0.102
Spring	`d1H`	0.623	0.518
	`rhL`	0.556	0.527
	`d1H` and `rhL`	0.669	0.286
Summer	`s1dL` and `t1H` and `d1H` and `rhL`	0.699	0.073

Table 3
La Silla results (1990–1992)

Season	Good seeing given...	Conditional possibility of good seeing	Possibility of variable(s) happening
Autumn	`t1H`	0.603	0.511
	`rhL` and `t1H`	0.697	0.353
Winter	`d1H` and `s1L` and `s1dL`	0.713	0.303
Spring	`t1H`	0.641	0.499
Summer	`s1L` and `s1dL` and `t1H`	0.588	0.346

Table 4
Unique environmental configurations for sets of cases studied

	Season	Number of unique combinations
Paranal	Autumn	137 out of 1077 cases considered
	Winter	118 out of 442 cases considered
	Spring	152 out of 1089 cases considered
	Summer	146 out of 958 cases considered
La Silla	Autumn	108 out of 676 cases considered
	Winter	111 out of 512 cases considered
	Spring	116 out of 688 cases considered
	Summer	127 out of 909 cases considered

Table 5
Contingency tables exemplifying estimated versus actual seeing values

Paranal

		Actual Seeing		
		bad	interm.	good
Estimated Seeing	bad	90	63	41
	interm.	39	67	62
	good	2	4	19

La Silla

		Actual Seeing		
		bad	interm.	good
Estimated Seeing	bad	69	62	21
	interm.	38	67	70
	good	3	11	29

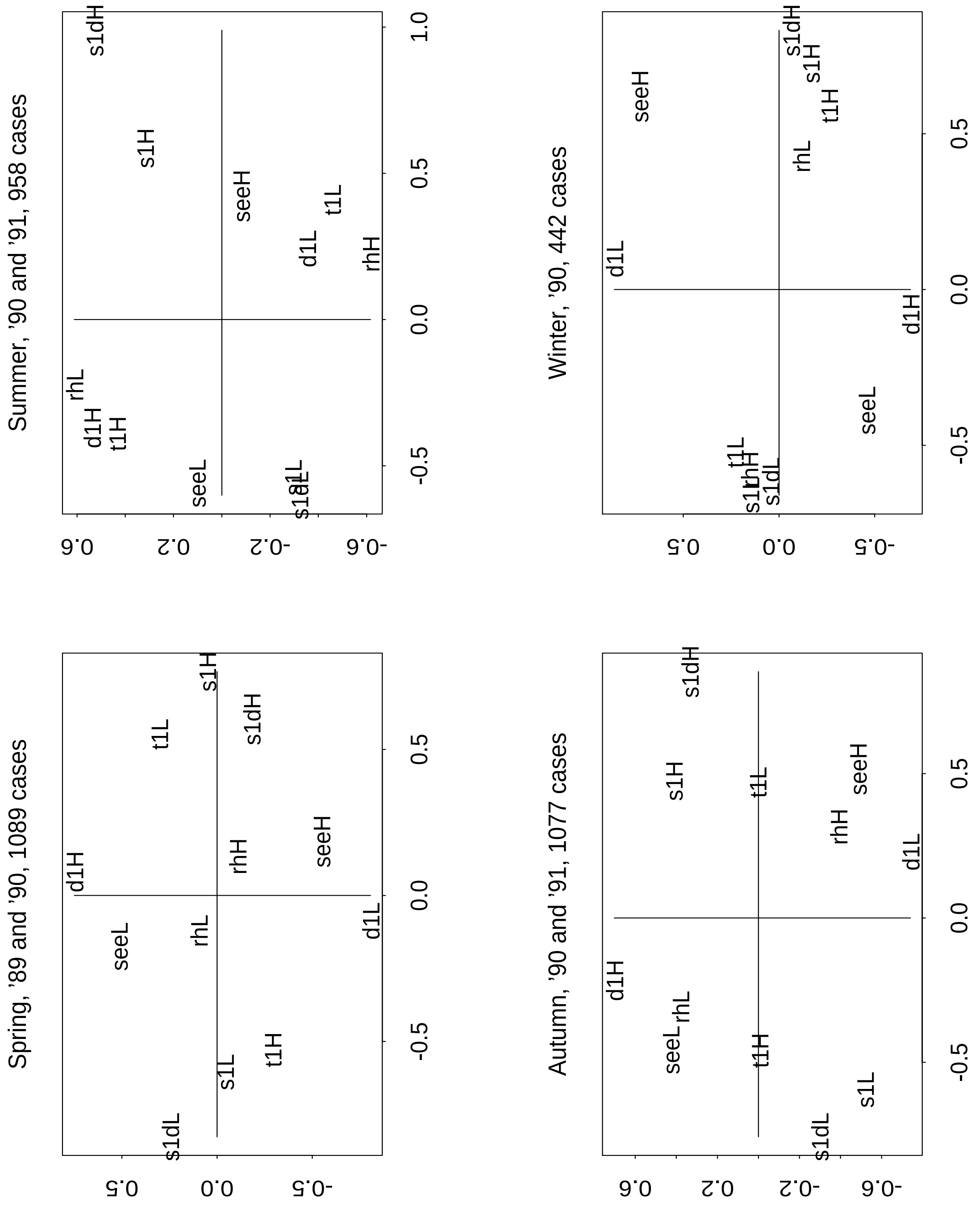

Figure 1: Paranal data. Principal plane of correspondence analysis, showing seeing and meteorological variables. L and H, at the end of the variable names (for which, see section 4), indicates "low" or "high". Fuzzy intermediate coding used.

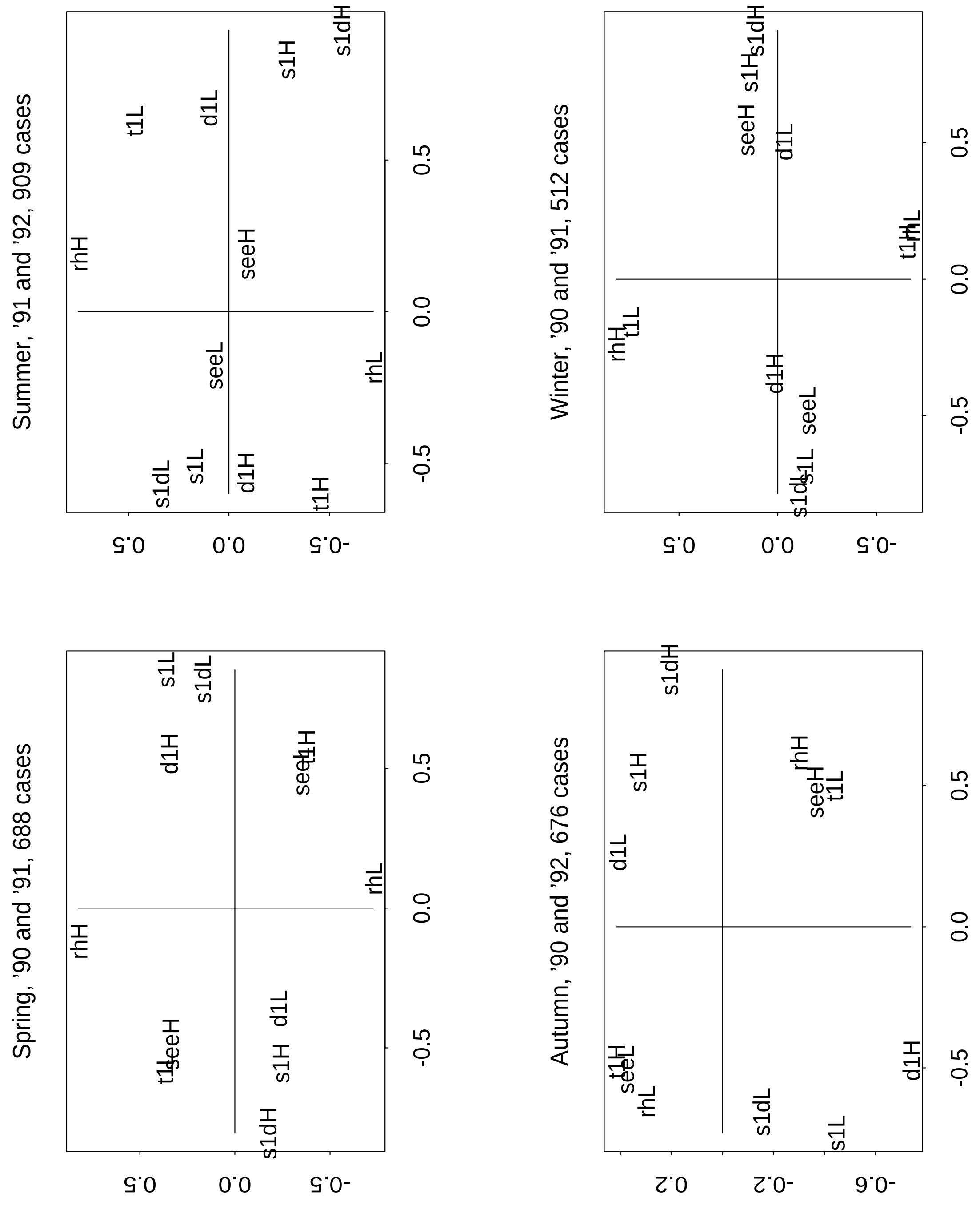

Figure 2: La Silla data. Principal plane of correspondence analysis, showing seeing and meteorological variables. L and H, at the end of the variable names (for which, see section 4), indicates “low” or “high”. Fuzzy intermediate coding used.

Figure 3: Diagrammatic interpretation of dependence of good seeing (`seeL`) on two arbitrary meteorological variables (`A` and `B`).

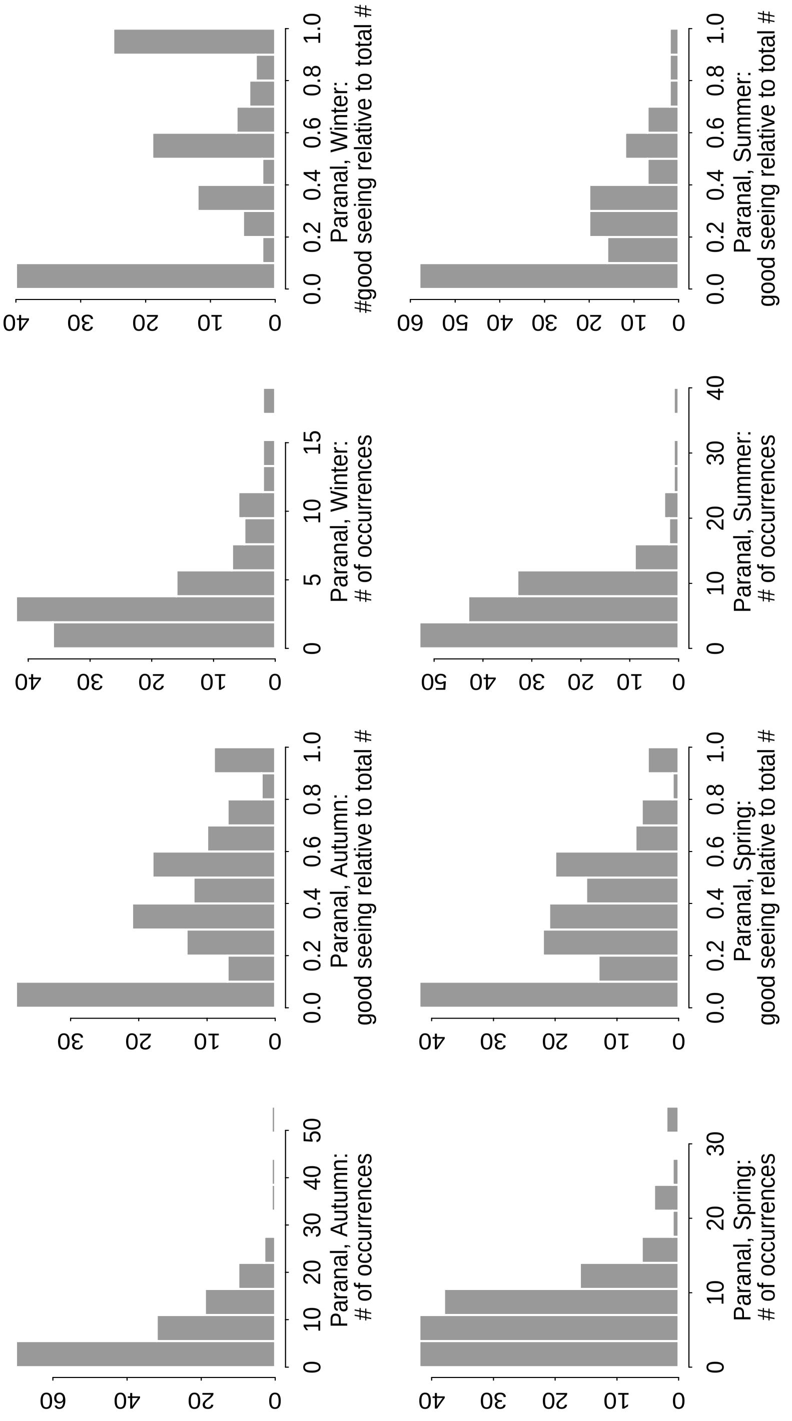

Figure 4: Paranal data. For each season: histogram of frequencies of unique environmental configurations; and histogram of relative frequencies of good seeing associated with these environmental configurations.

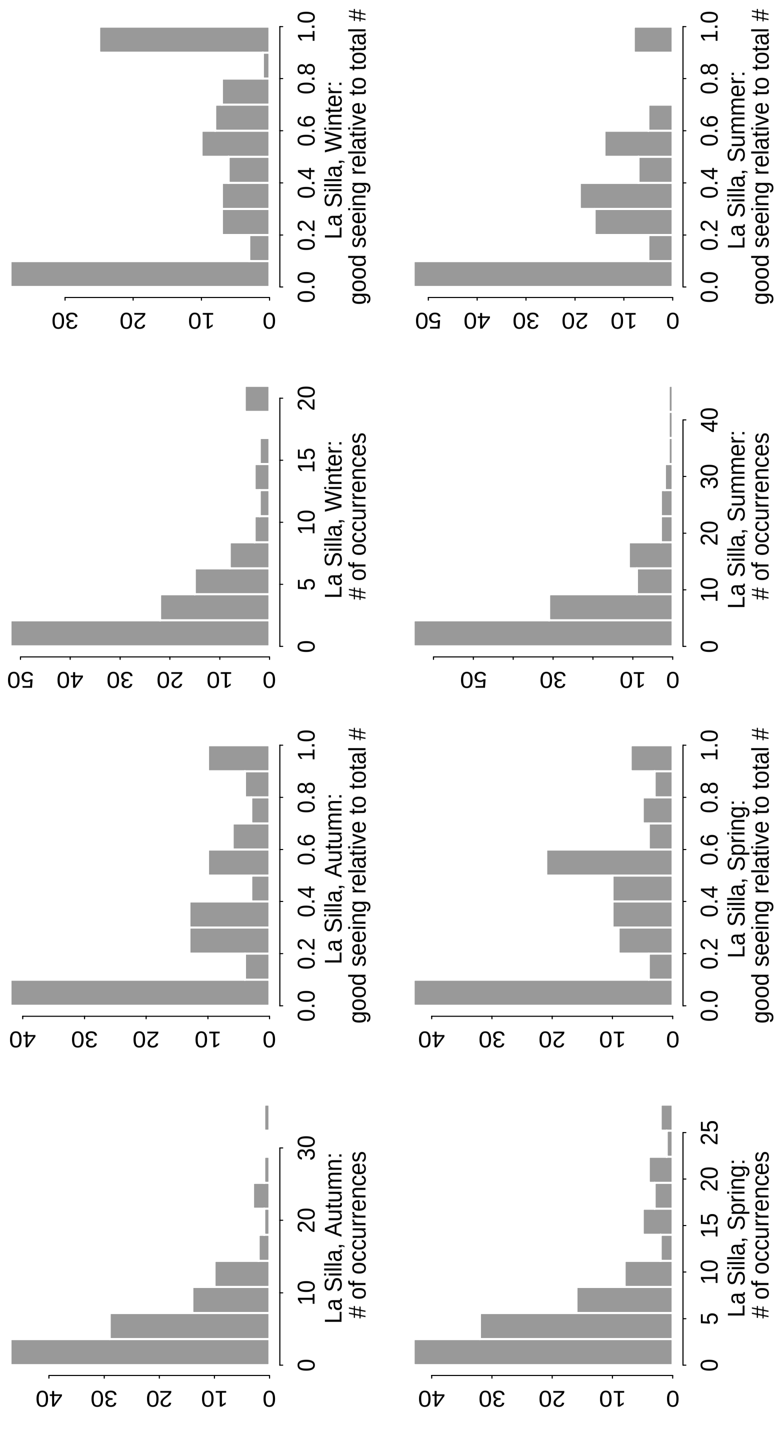

Figure 5: La Silla data. For each season: histogram of frequencies of unique environmental configurations; and histogram of relative frequencies of good seeing associated with these environmental configurations.