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Rainfall forecasting in tropical-equatorial environments: a case study of the Seychelles zone

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In tropical-equatorial environments, where weather has a high degree of variability, a reliable weather forecast is an essential decision-making tool. To achieve reliability and accuracy it is important to study both the climatological trends and the elements affecting the meteorological variables of the areas under analysis. A precise weather forecast is not enough, however. The way in which the information is presented to users in weather bulletins is also important. The users need to comprehend the forecasted meteorological synopsis and to draw relevant conclusions. In this case study a Medium Range Forecast model was used (NOAA Air Resources Laboratory MRF) to predict, in statistical form, the likely weather conditions. The verification of the weather forecast scored good results, especially in the shorter period (7 days), showing that this specifically designed weather bulletin was a reliable decision tool. In order to demonstrate the key role of the meteorological information to the decision-maker, an economic estimation of the weather forecasts was carried out.

1. Introduction

The DITIC Meteo Lab. at Turin Polytechnic was given the task of forecasting the weather of the Seychelles Islands by a private institution. This institution needed to work out in the open and accurate weather forecasts were crucial to the success of its operations. Since it was necessary to plan in advance all the activities, a Medium Range Forecast model was used. The institution asked for an 'operational index' of precipitation during the day, i.e. the time at which the event would start and the range of precipitation that was expected. This would allow the institution to schedule its daily activities in the most effective way.

The selected working period was from the middle of November to the middle of December 1999, on account of commercial needs. From a meteorological point of view, this is not the best time to start any kind of activity in tropical-equatorial areas. The Seychelles archipelago, located at about 5°S 55°E, has a high probability of precipitation in this period (Dhonneur 1986).

In this situation the weather forecast plays a key role in the planning process because most of the decisions are strictly dependent on what is stated in the weather bulletin. The specific working procedures adopted by the institution require highly reliable forecasts and a forecast that is tailored to its needs.

2. Methodology

The high variability of daytime precipitation in equatorial-tropical areas in the selected period (November–December) is likely to have negative effects on the quality of the final forecast (Del Prete et al. 1998). It is therefore important to understand the morphology and climatology of the area covered by the forecasts, in order to understand the trend of the relevant variables.

The Seychelles are located north-east of Madagascar in the Indian Ocean (http://go.hrw.com/atlas/norm_htm/seychell.htm). The total land area is about 455 km^2, with a coastline length of 491 km. The typical terrain condition is granitic (especially for the Mahè group) with narrow coastal strips. Of particular relevance for meteorological forecasting is the relatively high relief. The highest point is Morne Seychellois with a height of 905 m.

The climatological study was developed using a set of monthly precipitation data spanning 40 years, gathered by Dhonneur (1986), and the monthly precipitation data obtained by satellite measurements. The latter were obtained using the SSM/I sensor (Special Sensor Microwave/Imager), provided by the NOAA-NCDC.

Dhonneur's precipitation measurements were recorded at meteorological stations in equatorial zones, such as

Ouesso (1°37N 16°04E), São-Tomé (0°23N 6°34E) and, of particular importance in our case, Mahè (4°34S 55°27E) located in the Seychelles archipelago. The results (Figure 1) show a clear unimodal distribution of precipitation in Mahè with the rainy season usually beginning in September and ending in May.

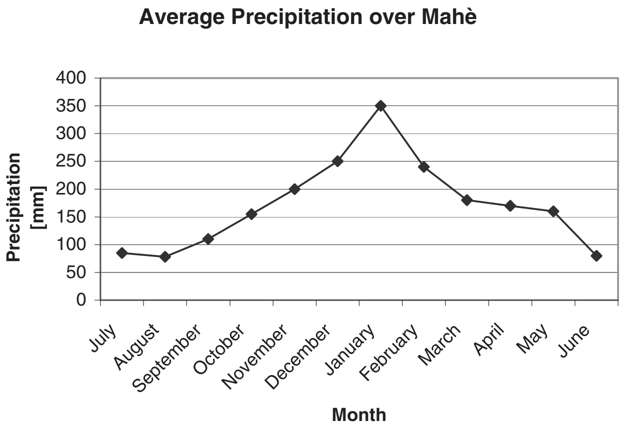

Figure 1. *Forty years' average monthly precipitation for Mahè–Seychelles (Dhonneur 1986)*

These results differ from the theoretical conclusion drawn by the same author for a generic equatorial zone. Generally the regions lying between latitudes 0° and 5° N or S are characterised by a bimodal distribution of precipitation because of the variation of the meteorological equator linked to the apparent movement of the sun. Differences between the conceptual scheme and the real data are often reported in equatorial case studies. By contrast, there is generally a more homogeneous correspondence between theory and reality for the tropical zones (Dhonneur 1986).

Figure 1 shows that the period considered has a monthly average precipitation between 150 and 200 mm for November, increasing in December to about 300–320 mm.

As a second step, the historical NOAA-NCDC meteorological database was consulted. The monthly precipitation measurements, derived with the use of the SSM/I (Special Sensor Microwave/Imager), were collected (Ferraro et al. 1994; Ferraro & Marks 1995).

The SSM/I rainfall algorithm developed at NOAA utilises the 85 GHz Vertical Polarization (V) channel to detect the scattering of upwelling radiation by precipitation-sized ice particles within the rain layer. The scattering technique is applicable over land and ocean. Rain rate can be derived indirectly based on the relationship between the amount of ice in the rain layer and the actual rainfall on the surface. Care must be taken to remove anomalous surface scattering features (e.g. deserts and snow). Additionally, over ocean, an emission rain algorithm, based upon the absorption of the upwelling radiation by rain and cloud water (at 19 and 37 GHz) is blended with the scattering algorithm.

A scattering-based global rainfall algorithm developed at the NOAA/SRL has been selected for use by the World Climate Research Programme/Global Precipitation Climatology Project (WCRP/GPCP) for land rainfall estimation. Monthly rainfall at 100 km and 250 km grids has been produced for the period July 1987 to the time of the analysis. Additionally, the instantaneous rain rate produced from this algorithm has recently been implemented by Fleet Numerical Meteorology and Oceanography Center (FNMOC) as the operational SSM/I rainfall algorithm.

A new version of the sensor with 2.5 degree resolution has been developed for use by the GPCP, and denotes regions of indeterminate rainfall due to the presence of snow and ice cover (updated as of January 1997).

Due to the failure of the 85 GHz channels during the period July 1990 to December 1991, no reliable retrievals can be made using the current algorithm. However, an alternate algorithm, which uses a 37 GHz scattering index over land and emission only over ocean can be used.

In addition to monthly rainfall estimates, the mean fractional coverage of rain (within a grid cell) can also be computed, which gives an indication of the relative frequency of rainfall. Finally, because the SSM/I measurements are made from a polar orbiting satellite, the estimates are subject to sampling errors. We can provide maps of the SSM/I sampling frequency for the month, which can be used to assess this sampling error.

This analysis was helpful to confirm the earlier data collected by Dhonneur and to understand more precisely the precipitation trend for the whole of the Seychelles archipelago.

As reported in other papers the algorithm used to interpret the SSM/I data leads to underestimation of the measurements along coastal zones and in tropical environments (Turk et al. 1998). Instead, Adler et al. (1993) have carried out a comparison of IR rainfall estimates and low-orbit microwave (MW) retrievals from the SSM/I, recognising the need for a more precise physical retrieval ensured by the microwave with respect to the IR cloud-top inference. Their focus, however, was on monthly rainfall means rather than on the very rapid update cycle needed to monitor deep convective storms.

In this case it is possible to confirm that the data obtained from the SSM/I were reliable and in relative agreement with Dhonneur's results (Figure 2). The differences occur mainly because:

- the precipitation data were based on a shorter period than those of Dhonneur (the available information begins in 1987) – which means that the most relevant phenomena could not be taken into account, leading to lower average monthly precipitation values;

- the spatial resolution of the SSM/I (100 km) is too low to take into account the relief effects over small islands;
- while Dhonneur's rain gauge measurements were recorded by actual observation on Mahè, the SSM/I values for Mahè are the result of an interpolation between two points on the measuring grid.

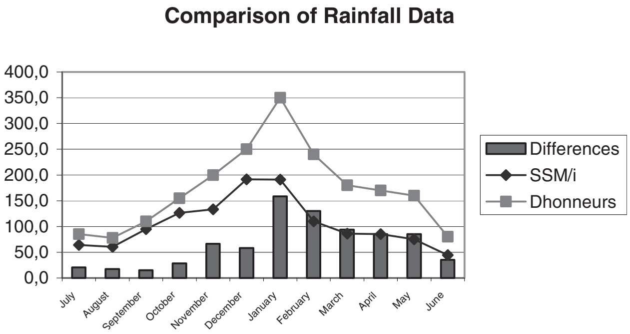

Figure 2. *Comparison of the average monthly precipitation derived from SSM/I data and the values obtained by Dhonneur (1986).*

This analysis allows us to define an equation of correction that has to be applied to the SSM/I rainfall measurements. The equation is directly derived by an exponential regression of the measured data (Figure 2). It has to be remembered that this equation can be considered reliable for an area of 120 km of the side defined by the following coordinates: 4°S–5°S, 55°E–56°E. This is the area where the two methods can both be used.

The equation is:

$$h_{pc} = 2.1 \cdot h_{pSSM/1}^{0.94} \qquad (1)$$

where $h_{pSSM/I}$ is the rainfall value measured by satellite and h_{pc} is the corrected rainfall value, defined by the rain measurements from the Mahè rain gauge.

The correlation coefficient r is equal to 0.87. The equation (1) is represented in Figure 3.

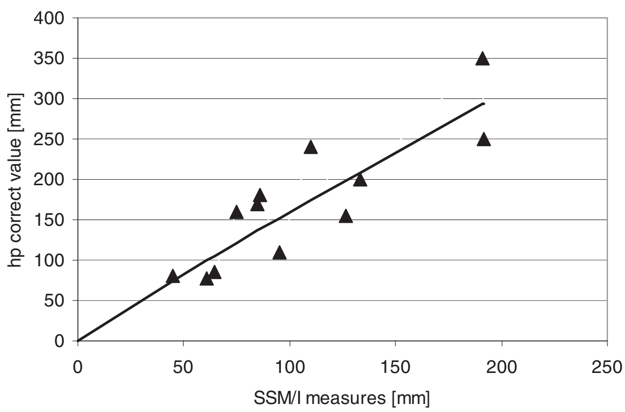

Figure 3. *Graphic of equation (1)*

The SSM/I derived images based on the monthly precipitation measurements, allows the computation of the daily precipitation as well, following the steps below.

From Figures 4, 5 and 6 it can be shown that the rainfall value, represented in the form of isohyet lines, has to be understood – given what is indicated by the NOAA-NCDC – as the cumulative value of the previous 30 days from the day under analysis.

The value of the nth day, found on the image, corresponds to:

$$S_n = \sum_{i=1}^{n} h_i \qquad (2)$$

For the following day the value is:

$$S_{n+1} = \sum_{i=2}^{n+1} h_i \qquad (3)$$

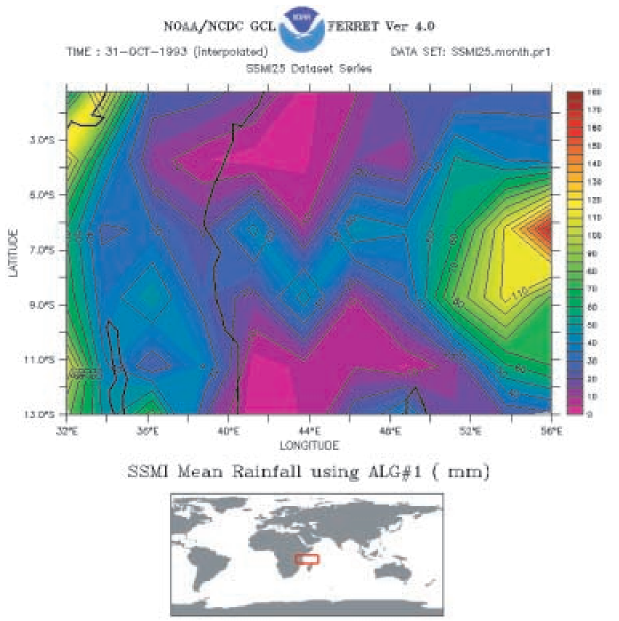

Figure 4. *Precipitation measured with the SSM/I sensors in the Seychelles area on the 31 October 1993 (see http://orbit-nt.nesdis.noaa.gov/arad2/index.html and http://www.saa.noaa.gov/cocoon/nsaa/products/welcome)*

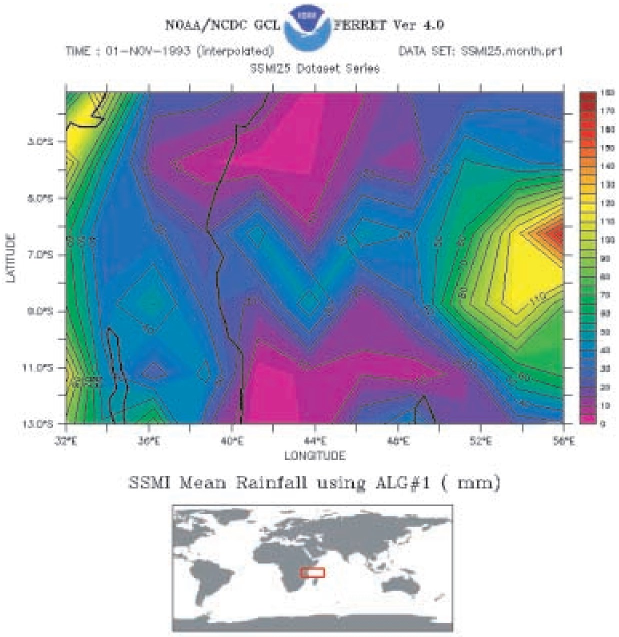

Figure 5. *Precipitation measured with the SSM/I sensors in the Seychelles area on 1 November 1993 (see http://orbit-nt.nesdis.noaa.gov/arad2/index.html and http://www.saa.noaa.gov/cocoon/nsaa/products/welcome)*

Given this, in order to obtain the rainfall height for the (n+1)th day, the rainfall value of day 1 has to be added, first of all, to equation (3).

Following the mobile average procedures (Wilks 1995), it can be stated, without a relevant error, that:

$$h_1 = \frac{\sum_{i=1}^{n} h_i}{n} = \frac{S_n}{n} \tag{4}$$

In this way the series, represented by equation (3), can be completed starting at day 1 until the day n+1. Eventually we obtain:

$$S^*_{n+1} = \frac{S_n}{n} + S_{n+1} \tag{5}$$

Finally, in order to obtain the rainfall amount of day n+1, we can subtract equation (5) from the expression (2).

After easy steps, we obtain:

$$h_{n+1} = S_{n+1} - \frac{n-1}{n} S_n \tag{6}$$

The factor $\frac{n-1}{n}$ is a constant equal to 0.967. The final solution is:

$$h_{n+1} = S_{n+1} - 0.967 \cdot S_n \tag{7}$$

As an example, Figures 7 and 8, based on the precipitation for 22 November 1993 and 23 November 1993, can be considered. Looking at coordinates 3.8°S and 53.8°E, the values are:

$$S_{n+1} = S_{23} = 45.8 \text{ mm} \; ; \; S_n = S_{22} = 46.7 \text{ mm} \tag{8}$$

Using formula (7), the rainfall value for 23 November 1993 is evaluated and found to equal $h_{n+1} = h_{23} = 0.64$ mm.

After these two steps, the climatological conditions of the area can be better understood.

The institution asked for medium-range forecasts to meet its planning needs (a 7–9-day forecast period). It was therefore decided to use the NOAA Air Resources Laboratory model 'MRF 191 km'. This is the model most widely used when forecasting weather over a medium range (10 days). The grid has a resolution of 191 km × 191 km on the entire globe and the operational assimilation system is based on the four-dimensional variational analysis, also called 4D-Var (Pezzoli 2001), as for the ECMWF model (Reading, UK). The MRF model can integrate all the principal atmospheric variables, such as pressure, temperature at different levels, wind speed and precipitation. The model was tested for a couple of days using measurements from the meteorological stations on Mahè and Praslin in order to get an idea of its advantages and limits. The results were good, showing that the model 'MRF 191 km' is able to forecast the meteorological trend with reasonable precision (see section 5 'Results and discussion', below), even in tropical-equatorial areas.

In conjunction with these methodologies, infrared, visible and water vapour Meteosat images (zone 6) were used to estimate the type and consistency of clouds on a large scale and thus to assess objectively the reliability of the MRF model (Bader et al. 1995; Georgiev and Martin 2001).

3. Details of the case study

Given the above considerations, it was decided that a document should be produced for the institution which would provide a climatological description of the area over the period in questions (November–December) and suggest the optimum time for commencement of their planned activities.

In this document was suggested that work should start as soon as possible, because rainfall amounts are increasing through November and December (Figure 1). More precisely, the satellite measurements indicate that, on average, the precipitation from 20 November to 27 November would increase from a weekly cumulative value of 120 mm to 140 mm. The following week (27 November–4 December) showed an even greater increase from 140 mm to 180 mm. For these reasons it was suggested that the institution's operations should get under way as soon as possible.

The next step was to specify, in the same document, the typical diurnal pattern of precipitation. This was particularly important for the institution because it required a clear picture of when its work could be carried out during the day. Precipitation is closely linked to temperature, wind and cloud coverage. Contrary to common belief, maximum rainfall values are not always recorded in the late afternoon as might be expected given the frequency of convective phenomena (storms and showers). In the case of islands with high relief, as in the Seychelles, precipitation is commonly observed in the early afternoon, followed by rapid dissipation of the clouds by the end of the afternoon. By contrast, for islands of low relief or with no nearby orographic influences, it is the difference between the ocean and the land (energy balance and friction with the ground) that causes local vertical circulation which can result in most rain falling at night, with a marked difference between the upwind and downwind coasts.

4. The weather bulletin

The final step was to define the requirements of a weather bulletin to meet the needs of the institution. A scientific meeting was set up before the beginning of the period concerned (around the beginning of November) to determine the optimal layout and contents of the bulletin. The main points were:

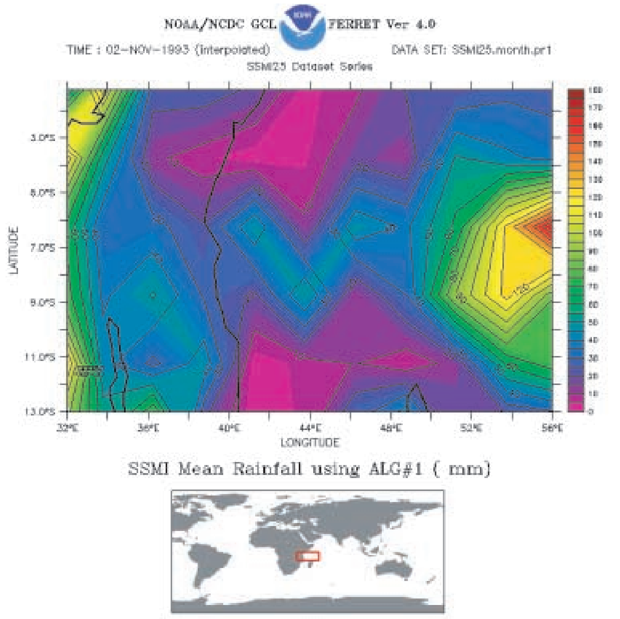

Figure 6. *Precipitation measured with the SSM/I sensors in the Seychelles area on 2 November 1993 (see http://orbit-nt.nesdis.noaa.gov/arad2/index.html and http://www.saa.noaa.gov/cocoon/nsaa/products/welcome)*

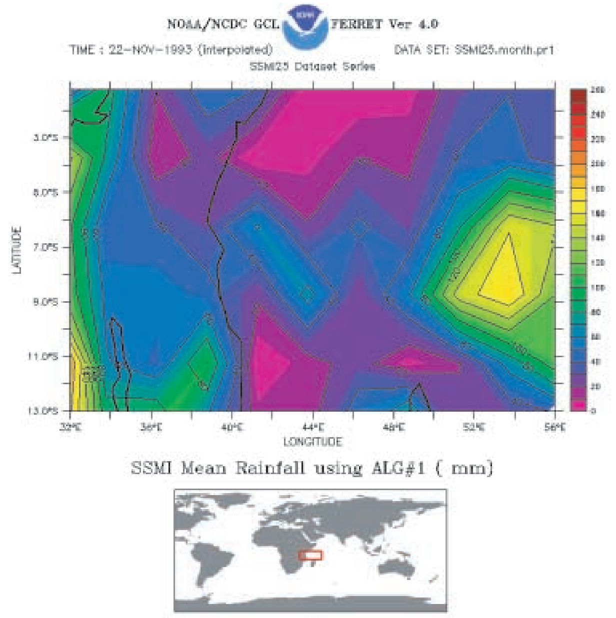

Figure 7. *Precipitation measured with the SSM/I sensors in the Seychelles area on 22 November 1993 (see http://orbit-nt.nesdis.noaa.gov/arad2/index.html and http://www.saa.noaa.gov/cocoon/nsaa/products/welcome)*

1. the use of an ‘Attention Level’, which is linked to the cumulative precipitation over 24 h. Four different levels were chosen to give the user an immediate idea of the amount of forecasted precipitation. The intervals were selected using a non-proportional range: more compact for low precipitation (the institution was able to work with no or low precipitation), and bigger in the case of high precipitation because in such circumstances no work would be possible.
    - Level 0: ‘meteorological calm’; precipitation 0–5 mm over 24 h;
    - Level 1: ‘meteorological awareness’; beginning of precipitation (storm); precipitation 5–20 mm over 24 h;
    - Level 2: ‘meteorological attention’; precipitation 20–50 mm over 24 h;
    - Level 3: ‘meteorological danger’; precipitation more than 50 mm in 24 h;
2. the use of an ‘Operative Index’. This index is a parameter used to show the probability of precipitation during the day. The day was divided into three time bands: 0000–0600 UTC; 0600–1200 UTC; 1200–1800 UTC. For each band a probability index of precipitation was calculated, based on the following scheme:
    - A: 0–10%
    - B: 10–40%
    - C: 40–70%
    - D: 70–100%

    In this case a smaller range was used for low probability levels of precipitation, in agreement with the demands.

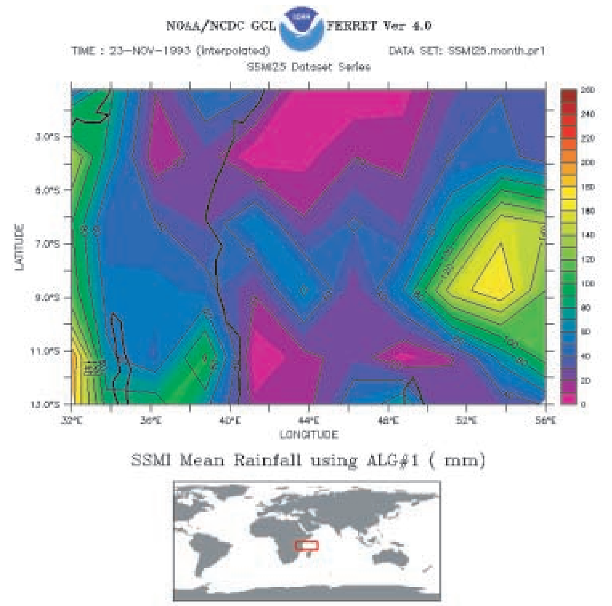

Figure 8. *Precipitation measured with the SSM/I sensors in the Seychelles area on the 23 November 1993 (see http://orbit-nt.nesdis.noaa.gov/arad2/index.html and http://www.saa.noaa.gov/cocoon/nsaa/products/welcome)*

3. the use of a ‘Technical Comment’ in which the forecasted weather conditions are described and the likely consequences for the institution are provided. This part is crucial for the interpretation of the weather bulletin; here it is possible to get a clearer definition of the boundary conditions that generate a certain weather situation and a more descriptive explanation of the meaning of the numerical indices reported before;
4. the use of a ‘Reliability Index’ (*RI*). This index is of particular relevance for the final user, as it indicates

how far the forecasted conditions are reliable, i.e. it acts as an additional decision-making tool when planning activities. The index is computed as follows (Del Prete et al. 1998):

- by considering the congruence of different forecasting models: the closer the interpretation of the meteorological forecasts offered by different models, the higher the level of reliability;
- by comparing the current weather situation with similar circumstances in the past;
- by comparing the current weather characteristics with the average values for that location.

The Reliability Index warns the forecast users that weather forecasts, especially on a medium-range level, are subject to errors and that the weather bulletin must be interpreted in terms of probabilities (Moch 1998).

Figure 9 shows the form that such a weather bulletin takes.

HYDRAULIC T.I.C. DEPARTMENT

TURIN POLYTECHNIC

METEOHYDROLOGICAL LAB

MRF WEATHER FORECAST – SEYCHELLES ISL. – PRASLIN

FOR THE DAYS 24, 25, 26 NOVEMBER 1999

ISSUED ON 18 NOVEMBER 1999 AT 1000 UTC

Weather situation on 18 November 1999, 0000 UTC: a heavy cloud mass is located over the Seychelles Islands. Rain and storms in process.

Forecast for 24 November 1999 (*RI*: 50–55%)

ATTENTION LEVEL: 1

OPERATIVE INDEX:

0000–0600 UTC: B (max C)
0600–1200 UTC: C (max D)
1200–1800 UTC: B (max C)

TECHNICAL COMMENT: the rainy season is under way and is characterised by the presence of cloud masses and showers in the afternoon. The cumulative precipitation over 24 hrs is about 15–17 mm. The average temperature is about 28 °C and relative humidity is 80–85%.

Forecast for 25 November 1999 (*RI*: 40–45%)

ATTENTION LEVEL: 1

OPERATIVE INDEX:

0000–0600 UTC: B (max C)
0600–1200 UTC: C (max D)
1200–1800 UTC: B (max C)

TECHNICAL COMMENT: as before

Forecast for 26 November 1999 (*RI*: 30–35%)

ATTENTION LEVEL: 1

OPERATIVITY INDEX:

0000–0600 UTC: A (max B)
0600–1200 UTC: C (max D)
1200–1800 UTC: B (max C)

TECHNICAL COMMENT: it seems that the meteorological situation is slowly changing. The precipitation will have a lower intensity and be concentrated in the afternoon.

The best solution, to be evaluated carefully by the technical staff, would be to start the activities on 25 November. In this way during the first two days it will be possible to carry out all the opportune surveying and to get acquainted with the weather conditions (sun in the morning, cloud at noon, rain – sometimes weak sometimes strong – in the afternoon). This time will be also helpful to organise the setting.

NEXT WEATHER REVISION BY EMAIL AT 1000 UTC 19 November 1999

Figure 9. *Weather bulletin*

5. Results and discussion

The following graphs compare the forecasted precipitation range with the measured precipitation at Mahè and Praslin, provided by the Seychelles National Meteorological Service. Note that 16th of November (date in which the decision wether to leave or stay was taken) was supposed to be the last day in which a weather bulletin had to be sent.

On the 17th the Institution, concened about the high variability of the meteorological conditions, asked for two other forecasts (for the 18th and 19th). For this reason there is one day missing in the graphs: in Figure 10 it is the 23rd, in Figure 11 the 24th, and in Figure 12 the 25th.

The results are satisfactory for a seven-day forecast (Figure 10), especially for the Mahè meteorological station. There is a relevant error during 24 and 25 November for Praslin, due to a wrong integration of the MRF model, quite common in these situations. In fact, even though Mahè and Praslin are relatively close (in comparison to the 191 km grid of the MRF model), their precipitation differed markedly (Mahè 16.6 mm, Praslin 96.0 mm on the 24th and Mahè 34.0 mm, Praslin 82.0 mm on the 25th), leading the model to work in critical conditions and, thus, with higher errors.

One suggestion is to control the 'Technical Comment' part of the weather bulletin, where it describes the atmospheric situation forecasted with suggestion tailored to the customer. Actually, for these specific days, the forecaster identified correctly the possible increase in the precipitation that could have been stronger in the central part of the day and suggested that surveying should start at the site in question (around Praslin) at that time, in order to be able to begin work on the 27th (Figure 11 and Figure 12), a day which was predicted to have a very low probability of precipitation. This suggestion was of paramount relevance, given that the rainy season was about to start, and, thus, all operations would have had to stop.

The model, in the case of the eight-day forecast period, produced worse results than the one obtained above, even though the general trend of precipitation fitted well (Figure 11). It can be seen that the model presents a major error on the 25th because it was not able to identify correctly the anomaly occurred. The cause of this error is the same as that listed above and the rapid change in weather conditions (the derivative of the measured precipitation in Praslin is really sharp) can be a problem for numerical models applied in a tropical-equatorial environment, creating other reasons for error.

It is interesting to note that the model integrated on the nine-day forecast is unable to indicate any trends in the weather pattern (Figure 12). For this reason, it is a good methodology to overlap, where possible, the

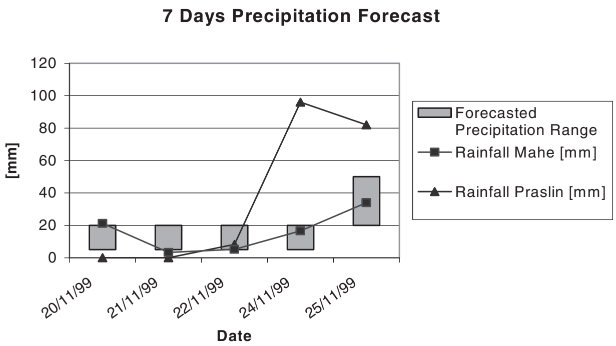

Figure 10. *Seven days forecasted precipitation. The 'date' label is day/month/year.*

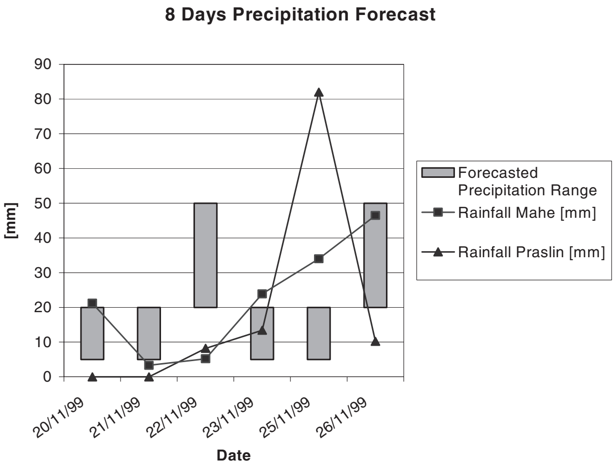

Figure 11. *Eight days forecasted precipitation. The 'date' label is day/month/year.*

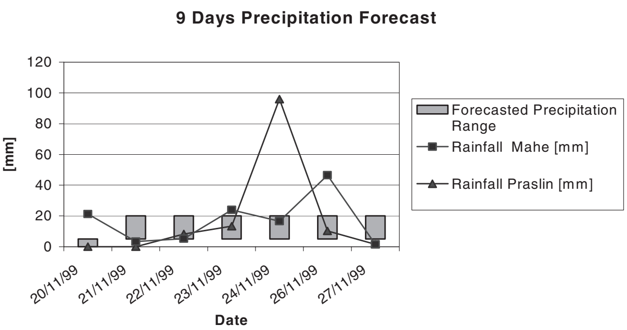

Figure 12. *Nine days forecasted precipitation. The 'date' label is day/month/year.*

meteorological trend obtained from the same model, integrated on different time ranges (7–9 days), in order to estimate the reliability of the model. This operation does not always lead to the formulation of clear conclusions on the results, but could be an efficient control system, especially when higly variable weather conditions take place. As a consequence, the Reliability Index for the eight- and nine-day forecasts was low, around 30%, because of all the problems pointed out above.

In order to interpret these results correctly it is necessary to read the Technical Comment provided for each forecasted day. This is a crucial point of the weather

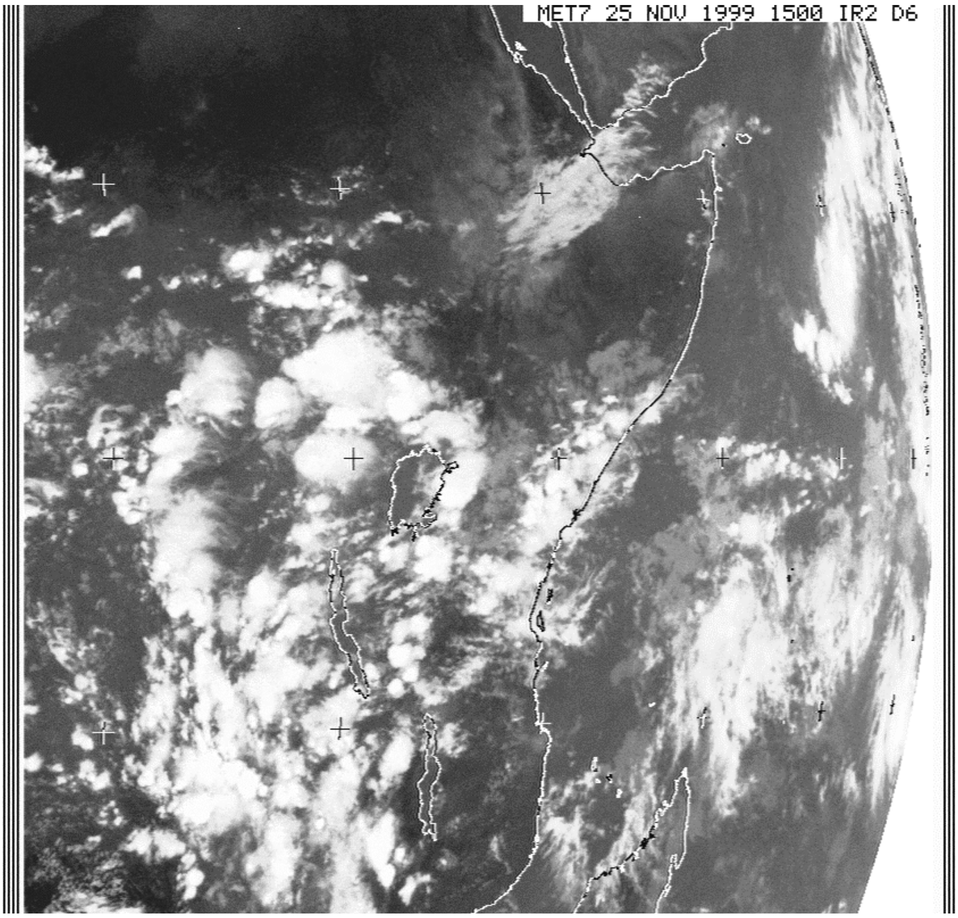

Figure 13. *Meteosat image IR of the 25/11/1999 15.00 UTC*

bulletin, because it allows the user to understand which kind of weather pattern is expected to occur and why, expressed in a descriptive way. Furthermore, the forecaster gives a deeper description of the meteorological situation, as compared to using only numerical values, and suggests which part of the day is recommended for certain activities.

It has to be pointed out that the precision obtained for Mahè is higher because of the availability of better data, such as the measurements gathered by Dhonneur (1986). Armed with this precise information the forecaster can provide a more reliable weather forecast, especially in the long term.

Finally, Figure 13 shows the Meteosat image in the infrared window of 25 November 1999, received by the DITIC Meteohydrological Laboratory of Turin Polytechnic. As indicated in the previous graphs, 25 November 1999 was critical for the MRF model due to the highest discrepancies between the model and the measurements. In the Seychelles area it is possible to find clouds of thermo-convective origin which are characteristic of the intertropical band called ITCZ (Hsu 1988). Associated with these clouds there is usually strong rain activity. Figures 10 and 11 show that the cumulative daily rainfall amounts recorded by the rain gauge at Praslin were equal to 82.0 mm.

6. Economic evaluations

In this section, which follows the prototype decision-making models proposed by Katz & Murphy (1997), we show that even inexpert users of weather forecasts that incorporate a Reliability Index (Figure 9) can organise their operations in a cost efficient way.

Furthermore, it has to be taken into account that the weather forecast had a strategic relevance for the business because it was consistently generated on a medium-range basis (at least seven days). The institution based its activities on this weather forecast, a decision that involved the cost of the transfer of people and material from Italy to the Seychelles, plus the eventual extra costs of lodging in case of bad weather.

A contingency table (Table 1) was used (Murphy 1977; Mylne 2002); the costs, in €/day, were provided by the institution.

Table 1. *Contingency table (€/day)*

Forecast		Stop the work	
		Yes	No
Weather situation	Yes	H	M
(rain)	No	F	R

In Table 1 the costs are:

- *H* (Hit): 3700 €/day
- *M* (Miss): 15000 €/day
- *F* (False Alarm): 8700 €/day
- *R* (Correct Rejection): 2500 €/day

The costs include the wage costs of the personnel and the transportation of the required machinery. In addition, for any decision taken ('stop the work' or 'not stop the work'), there is a fixed cost linked to the compensation that has to be given to the staff once the project gets under way. In the case of 'stop the work', the costs of postponing activities already organised must also be incorporated. The costs in Cell *R* – 'don't stop the work' and 'no rain' – are not equal to zero because additional costs have to be considered. In fact, if work goes ahead, the workers must be given full wages, which causes a relative increase in the overall costs. If it is decided to start operating and rain occurs (Cell *M*), then major costs have to be considered, owing to delay and possible damage to the instrumentation. However, most companies that undertake outside operations are usually covered by insurance in order to reduce the financial risks involved in making the wrong decision.

Using this contingency table, a pay-off analysis can be derived (Thornes & Stephenson 2001), as follows:

- Cost to stop the project:

$$C_S = [3700 \cdot P + 8700 \cdot (100 - P)]/100 \quad (9)$$

- Cost to undertake the project:

$$C_U = [15000 \cdot P + 2500 \cdot (100 - P)]/100 \quad (10)$$

In equations (9) and (10), *P* represents the probability that a certain meteorological event will occur and it is coincident with the Reliability Index (*RI*) of the weather forecast reported in the bulletin.

Considering the weather bulletins, where a probabilistic approach is used, the average Reliability Index is about 45%.

Substituting this value (P=RI=45) into formulas (9) and (10), the total costs evaluated are equal to:

C_S = 6450 €/day

C_U = 8125 €/day

From here it is possible to understand that the decision to undertake the project anyway could lead to relevant adjunctive cost, demonstrating the importance of a good weather forecast.

The critical probability P_C, the minimum probability from which it is economically convenient to consider the weather forecast suggestions, can be easily derived equalising the formulas (9) and (10):

$$P_C = \frac{2500 - 8700}{3700 - 8700 - 15000 + 2500} \cdot 100 = 35.4\% \cong 35\% \quad (11)$$

The result is lower than the Reliability Index usually obtained in the weather bulletin.

It is also clear that with this kind of medium-range forecast (7–12 days) where $\bar{P} \cong 45\%$, the final user will consider it more convenient to postpone the operation, and thus the departure for the destination site, and wait for better meteorological condition.

Nevertheless the Reliability Indices for the eight- and nine-day forecasts were around 30% and the P_C calculated by equation (11) is higher in comparison with this *RI*, in line with what has been said in section 5 (the results of the MRF model for day 8 and 9 it is not satisfactory). For these reasons, and given that the costs of undertaking the project are normally higher than the costs of stopping the project, it is important to use the results of the deterministic atmospheric models to prepare the forecasts with a maximum time range of 6–7 days, especially for the complex zones in tropical-equatorial areas. The use of the 'Ensemble Prediction System-EPS' (Toth & Kalnay 1993; Molteni et al. 1996; Buizza & Palmer 1998) will help the meteorologist prepare the probability forecasts in a more reliable form over the medium range of 8–10 days (Toth et al. 1997; Mylne 2002).

7. Conclusion

Weather forecasts have demonstrated their utility in decision-making processes. It has been suggested that MRF forecasts should be expressed in a probabilistic manner if they are to be useful to final users, because of the high level of uncertainty, especially when applied in a tropical-equatorial area. Nowadays, many meteorological services (such as Météo-France) use a probabilistic approach to MRF forecasts because is one possible technical solution to have a more reliable long term forecast. The ways of measuring the probability of a certain meteorological event (in our case the Reliability Index) might differ, but the point is to express a congenital degree of uncertainty in the weather forecast. The Reliability Index should be a key point in the assessment of the economic value of weather forecasts. It is thus an important criterion for the decision-makers, who must weigh up the consequences of trusting the weather forecast (Katz & Murphy 1997).

Once more, it is important to stress the paramount importance of a flexible weather bulletin tailored to the user's needs. A weather forecast that presents its data in a confusing way is of little use. The layout and the type of information provided in the weather bulletin have to be agreed at an early stage with the user (in this case, the institution). This requires the forecaster to focus on the user's needs, and to simplify where necessary the information provided.

It has to be underlined that this paper seeks to represent a basic approach to work with management problems even in case of extreme events. Using Table 1, the cost-benefit matrix can be defined as:

$$[A]=\begin{pmatrix} c_1 & l_1 \\ c_2 & l_2 \end{pmatrix} \tag{12}$$

where l_2 can be also considered, in particular cases, equal to zero.

Working with more complex problems that can have different socio-economical impacts on the environment, it is necessary to create preliminary vectors $\boldsymbol{c_i}$ and $\boldsymbol{l_i}$ defined as:

$$\boldsymbol{c}_i=\begin{bmatrix} x_{i1} \\ x_{i2} \\ \dots \\ \dots \\ x_{in} \end{bmatrix}, \boldsymbol{l}_i=\begin{bmatrix} y_{i1} \\ y_{i2} \\ \dots \\ \dots \\ y_{in} \end{bmatrix} \tag{15}$$

These indicate the global cost and loss. These vectors can then be inputted in the matrix $[A]$ (see eq. (12)) to obtain the total cost analysis (Grilli 1999).

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