Meteorological Forecasts for the Southern African Large Telescope (SALT):

Phase 1

Setup and Maintenance of an Automated System for Operational Forecasts

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Interim Report

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1. Introduction

Work towards setting up and providing operational meteorological forecasts for the Southern African Large Telescope (SALT) was started in March, 2003. The first phase includes:

- (i) Obtaining data from an operational numerical meteorological forecast model in real-time mode
- (ii) Obtaining meteorological observations from the Sutherland Observatory weather station in real-time mode
- (iii) The development of a forecast programme (algorithms, code and scripts) to process the data and produce forecast products
- (iv) Provision of daily forecasts for a one year period and the compilation of a database of meteorological model and on-site meteorological data (for future evaluation of the forecast accuracy)

The first phase of providing operational forecasts for SALT will address the primary forecasts needed to support SALT operations. These include forecasts of near-surface air temperature, dew point (or relative humidity), wind speed, wind direction and low pressure events.

The system for providing the forecasts will be fully automated. UNIX/LINUX scripts will be written to download or upload the necessary data, run the forecast programme and provide the forecasts in suitable format to users.

The first version of the forecast programme has been run in operational mode since 10 November, 2003. The forecasts may be viewed at: www.saao.ac.za/~saltmet/.

This report describes the work completed thus far, current status of the forecast system and what remains to be done in phase 1. Section 2 provides details on the data used as input to the forecasts (item (i) and (ii) above). Section 3 describes the development and current status of the forecast programme. Section 4 presents an evaluation of forecast accuracy for the period April - October, 2003 for the parameters temperature, pressure and relative humidity. Section 5 outlines the work yet to be done in phase 1.

2. Input data

2. 1 Numerical meteorological forecast model data

Numerical meteorological forecast models of the atmosphere are run daily and provide the basis for routine weather forecasts provided by national weather services. Global models are run on an operational basis by two main centres – the European Centre for Medium-range Weather Forecasting (ECMWF) in Reading, England and the National Centres for Environmental Prediction (NCEP) in Camp Springs, Maryland, U.S.A.. National weather services sometimes run regional forecast models which are initialized using data from the global models. The South African Weather Service (SAWS) runs the regional model known as **Eta** on an operational basis for southern Africa.

The regional Eta model for southern Africa, as run by the SAWS, uses a horizontal resolution of 32km. In the vertical, a modified terrain-following co-ordinate system is used with 45 levels. Output is interpolated to a grid at 1^{o} x 1^{o} resolution in the horizontal and 50 mb (or hPa) resolution in the vertical. For the purposes of the forecasts to be generated for Sutherland Obsevatory output is obtained for 9 grid points surrounding the observatory (Figure 1). In the vertical, data are obtained for levels above the surface (as defined in the model topography) to 100 mb (approximately 18km). The forecasted parameters are: geopotential height (m), temperature (^{o}C), specific humidity (g/Kg), relative humidity (%) and component winds (m/s). The model is run twice daily, with initialization times of 00UT and 12UT. Forecasts are produced at 6 hour intervals to 48 hours ahead.

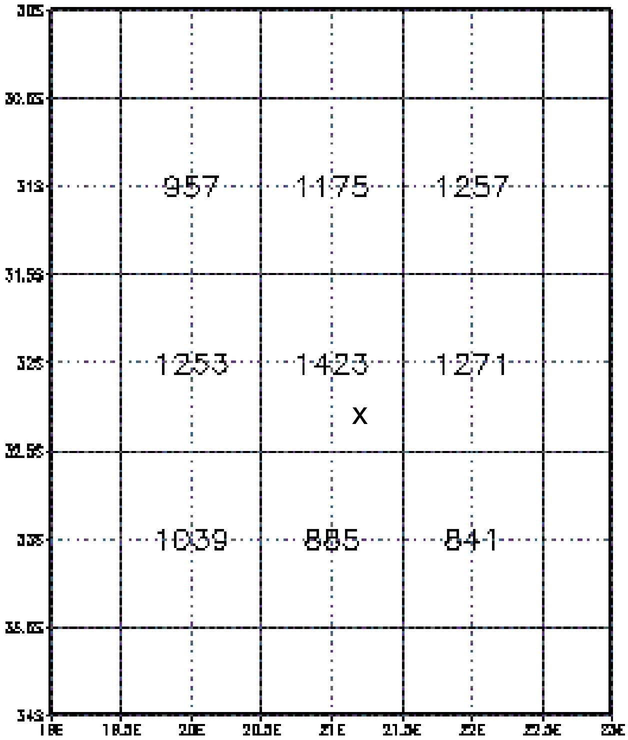

Figure 1. Model grid and terrain heights (m) for the area around Sutherland Observatory (32^{o} 23' S, 20^{o} 49' E, Altitude 1760m).

Since the model is initialized with data collected, for example, at 00UT some time elapses between the observation time and when the data are available at the processing site. Additionally, the model takes time to run. The result is that the forecast output from the model becomes available about 6 hours after the initialization time.

The data as described above are being received in real-time mode from the SAWS. Currently the data are archived on a server at SAAO where the forecast programme is under development. Receipt of the data and archiving started in April, 2003.

(Note: As from 15 December, 2003 Eta model surface output for the parameters mentioned above have been added to the data stream received from the SAWS. These data have been added to see if the model can provide useable information on the temperature cycle near the ground. See sections 3 and 4.)

2.2 Surface observations from Sutherland Observatory

It was proposed that surface observations from the weather station at Sutherland Observatory would also be used as input to the forecast programme. Additonally, these data are used to test the accuracy of the forecasts. The weather station was installed and is maintained by SALT. The measured parameters are: pressure (mb), dew point (^{o}C), relative humidity (%), wind speed at 30m (m/s), wind direction at 30m (degrees from N), wind speed at 10m (m/s), wind direction at 10m (degrees from N), temperature at 2m (^{o}C), temperature at 5m (^{o}C), temperature at 10m (^{o}C), temperature at 15m (^{o}C), temperature at 20m (^{o}C), temperature at 25m (^{o}C) and temperature at 30m (^{o}C).

Archiving these data started in April, 2003 and the archive is currently being updated each month by SALT. In the period April to October, 2003 there are several sizable (1-2 weeks long) gaps in the data. Available data for these months were used to evaluate the accuracy of the forecast programme as presented in section 4.

At the time of writing of this report, surface weather observations from Sutherland Observatory are not being used in the operational forecasts provided at: www.saao.ac.za/~saltmet/. There are two reasons for this. Firstly, the provision of the surface weather station data in real-time mode has only recently become reliable (measurements and data posting). Secondly, the forecast programme code (Kalman filter approach) which uses the surface weather station data in the forecast has thus far found to be of little value in improving the accuracy of the forecasts. Other options for the use of the surface data in the forecast are therefore under consideration (see section 4 and 5).

3. Development of the forecast programme

Development of the forecast programme code was undertaken in two stages. The first stage involved the use of the Eta model data from the SAWS. To determine the forecast parameter values at the site the four closest grid points in the Eta model domain are used (see Figure 1). Horizontal interpolation is performed inversely proportional to the distance between the site and the grid point. Vertically, values are interpolated using the data from the two constant pressure levels immediately below and above the *actual site altitude of 1760m.*

The relationship between height and pressure is defined by the hypsometric equation as follows:

$$Z_2 - Z_1 = (R_d T_v / g_0) \ln (p_1/p_2) \qquad (1)$$

Where Z_1 and Z_2 are, respectively, the geopotential height at the base and top of an atmospheric layer with corresponding pressures p_1 and p_2, R_d is the "gas" constant for dry air, T_v is the mean virtual temperature of the layer, g_0 is the globally averaged acceleration due to gravity (taken as 9.8 m/s) and ln is the natural log function. Below 5km the difference between the geopotential height and geometric height is less than 0.1%.

Using equation (1) the surface pressure equivalent for Sutherland Observatory is determined. In the atmosphere pressure is proportional to mass so the remaining parameters are interpolated using pressure as the vertical co-ordinate. Temporal interpolation between the 6-hourly forecasts to one hour increments is performed linearly. Parameter values derived in this manner are the basis for the forecasts at the present time.

In the Eta model topography, the surface terrain for Sutherland Observatory is considerably lower than the actual terrain height. Since the parameter values forecasted using the Eta model data are based on the actual site altitude, the values are indicative of the free air at this altitude. In other words, surface effects are being underestimated. For temperature, in particular, these surface effects are often significant. As air flows over the surface it becomes turbulent and heat exchanges between the air and the ground occur. This cools the air near the ground at night and warms it during the day. During the day, heating of the air near the ground is greater than the cooling effect at night since the daytime thermal stratification enhances the turbulence.

During the day, therefore, actual near-surface air temperatures will be greater than the temperature forecasts based on the Eta model data. At night the opposite would be true but to a lesser degree. This effect is clearly seen in Figure 2 which shows the observed 30m temperature at Sutherland Observatory and the temperature forecast based on the 00UT run of the Eta model for each day. Between 11h00 and 18h00 SAST there is a sharp spike in temperature associated with daytime heating. Interestingly, at night, significant cooling occurs only on rare occasions (when there is little or no wind). In most instances, night-time temperatures do not differ significantly from the temperature forecasts based on the Eta model output. This bodes well for the SALT forecasts since night-time temperatures are clearly of primary importance.

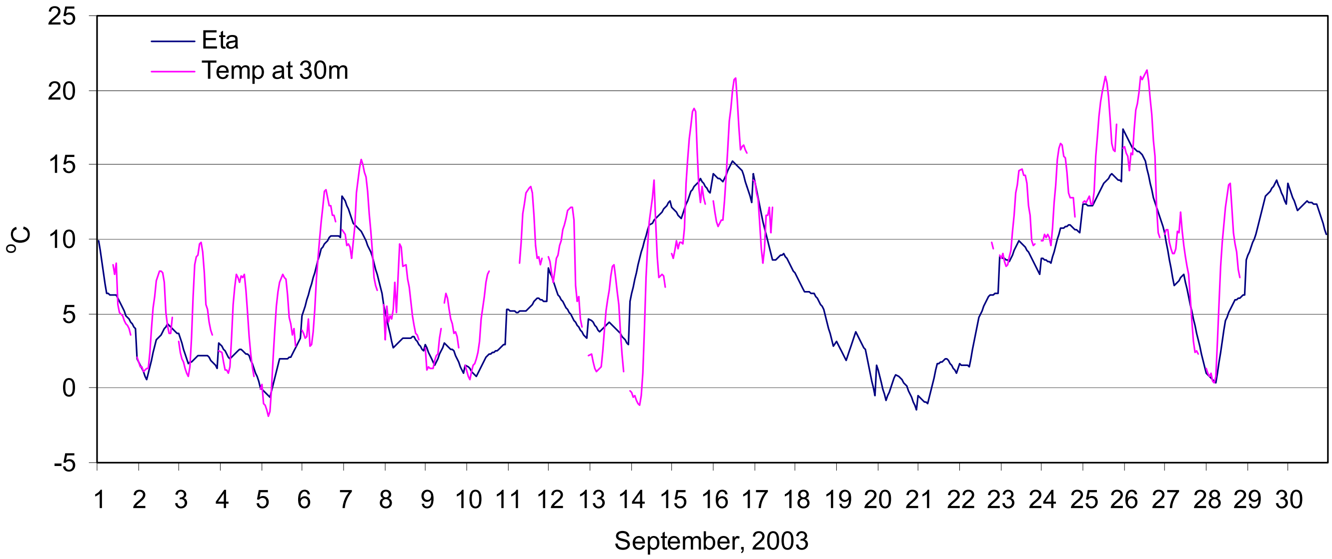

Figure 2. Temperature at Sutherland Observatory for the month of September, 2003 using hourly data. The Eta values are based on the 00UT model run for each day.

It was intended that the surface temperature observations made at Sutherland Observatory would be used to provide information on the daily cycle of temperature near the ground and that this information would be used to modify the forecast based on the Eta model output. The proposed approach involved the application of a Kalman filter.

Observations of temperature and Eta model temperature forecasts made over seven days prior to the forecast period were used to train the Kalman filter. Hourly temperature values were used. To begin with the observations (persistence) and Eta forecasts were given equal weight in the state vector. Thereafter the Kalman process takes over and adjusts the weights. It was found that the manner in which the weights were adjusted in the Kalman filter helps the forecast accuracy in the first 9-10 hours after initialization but is detrimental later in the forecast period (see section 4). The possibility of training or using the Kalman filter differently is being investigated further.

4. Evaluation of forecast accuracy

Surface observations made at Sutherland Observatory over the period April-October, 2003 were used to determine the accuracy of the forecasts made over the same period using the Eta model only and the Eta model in combination with the Kalman filter approach. This report includes an evaluation of forecast accuracy for temperature, pressure (the basis for forecasting low pressure events) and relative humidity. The evaluation for wind speed and wind direction is still in progress.

The 24-hour carbon copy forecast provides the first point of reference. This is the forecast based on the assumption that whatever is observed today at a particular hour is the forecast for the same time tomorrow. The accuracy for the forecasts based on the Eta model and Eta model plus Kalman was determined for the 00UT model run. This run was used in the evaluation since the forecasts based on it will be of primary importance when forecasting for SALT operations. (The 00UT model run output becomes available at 06UT, giving a lead time of 10-12 hours before SALT starts to operate in the evening. A forecast for the start of SALT operations the following evening is also provided). The forecasts were compared for the hours extending from the initialization time to 48 hours ahead at one hour increments. For the *in situ* data hourly values were computed as the mean of observations from 10 minutes before the hour to 10 minutes after the hour. Output from the forecast programme is in increments of one hour since the 6-hourly Eta model forecasts are interpolated to one hour intervals before being used as input to the forecast programme.

4.1 Temperature

Figures 3 and 4 show the differences (mean absolute and root mean square) between the observed and forecasted temperatures for the different forecasting methods. The figures shown are for the temperature at 15m above the ground. The plots for the temperature at 30m above the ground are essentially the same. Overall the forecast based on the Eta model output only, performs best. Use of the Kalman filter only improves the forecast in the first 10 hours. This is of very limited value since the critical forecast hours are from 17 to 29 hours (the observing night) after the initialization time.

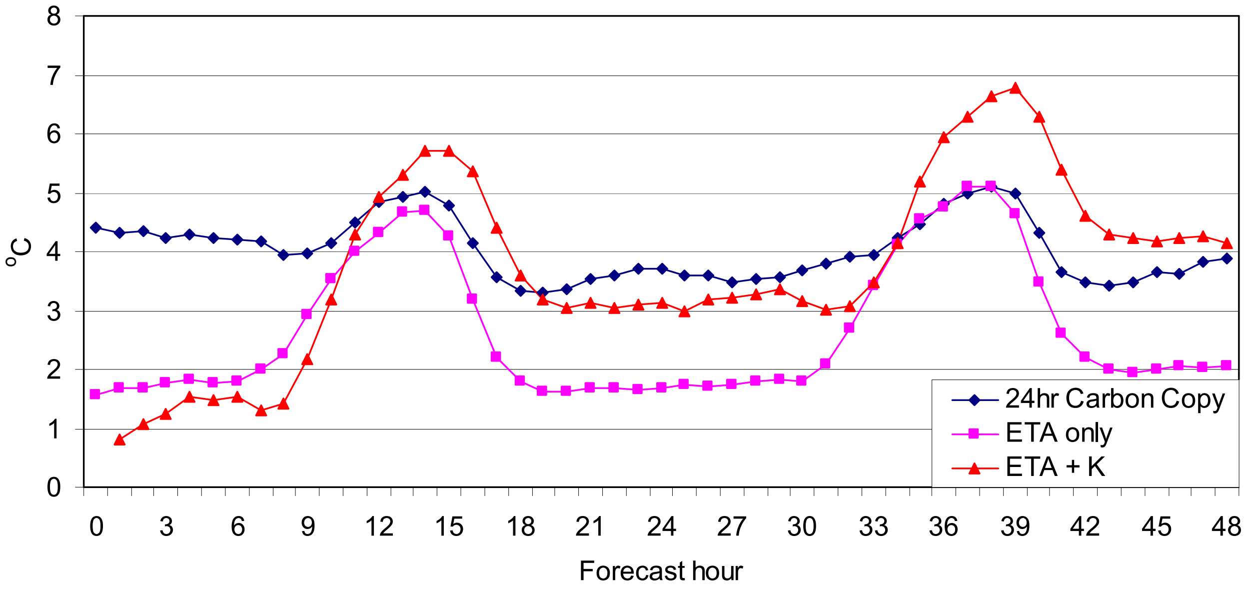

Figure 3. Mean absolute difference between observed and forecasted temperature at 15m for three forecasting methods.

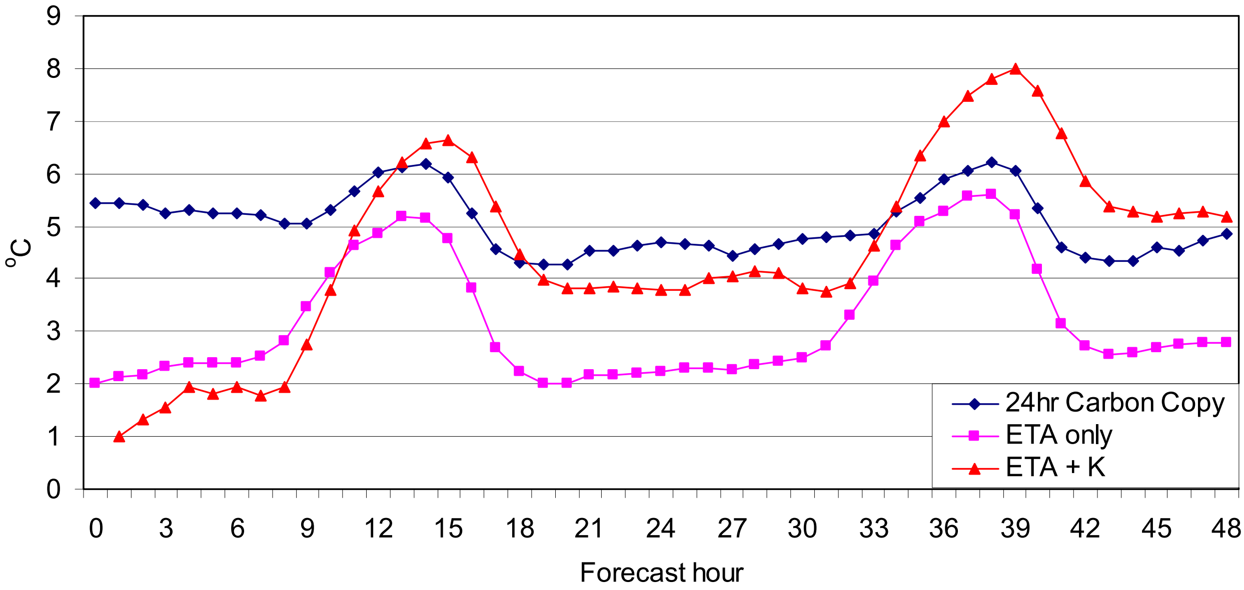

Figure 4. Root mean square difference between observed and forecasted temperature at 15m for three forecasting methods.

As was noted in section 3, the higher temperatures during the day between about 11h00 and 18h00 local time are not well forecasted due to the fact that, in the Eta model data used here, surface heating effects have essentially been excluded. The forecasts based on the Eta model output only perform well for night-time hours with a mean absolute difference between observed and forecasted values of less than 2°C. The RMS difference is just above 2°C. Particularly encouraging is the fact that the forecast accuracy does not change much during the first observing night in the forecast period. Even for the second observing night the forecast accuracy does not deteriorate significantly. It is quite clear that the carbon copy forecast is significantly worse with differences of 4-5 ^{o}C.

Use of the Kalman filter was expected to help with forecasting the warm daytime temperatures (and cold night-time temperatures). However it was found that this is only the case for the first 9-10 hours after initialization. For the forecast initialized at 12UT (Figure 5) the improvement made by Kalman is quite dramatic. However after the first 9-10 hours using the Kalman filter is counter-productive. The reason for this was investigated. At the start of the forecast period persistence (of observations) and Eta model output values are given equal weight in the state vector. However, since the persistence forecast is much closer to the observed values than the Eta forecast directly after the initialization time, within a few hours of training the Kalman process gives much more weight to persistence than the Eta model output. This helps forecast accuracy in the first 9-10 hours but is detrimental later in the forecast period. The possibility of training the Kalman filter differently is being investigated further. Other methods for improving the forecast accuracy during the daytime are also being considered. See section 5.

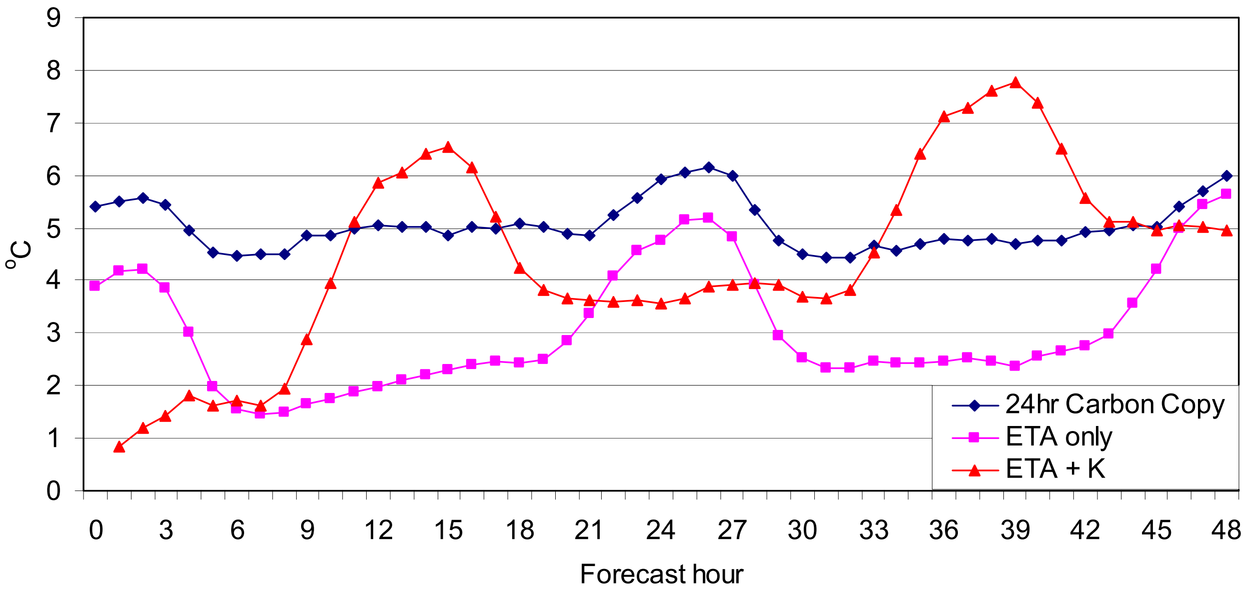

Figure 5. Root mean square difference between observed and forecasted temperature at 15m for three forecasting methods. Forecast initialized at 12UT.

4.2 Pressure

Differences between the observed and forecasted atmospheric pressure for the different forecasting methods are shown in Figures 6 and 7. Overall the forecast based on the Eta model output performs best. Use of the Kalman filter improves performance in the first 12 hours. Forecasting pressure is important in so far as it relates to the forecasting of low pressure events. These events are typically associated with bad weather (rain, snow and high winds). For the 00UT run of the Eta model the critical forecast hours would be those till the end of the observing night (0-30hrs). For this period the forecast accuracy for pressure is better than 2mb.

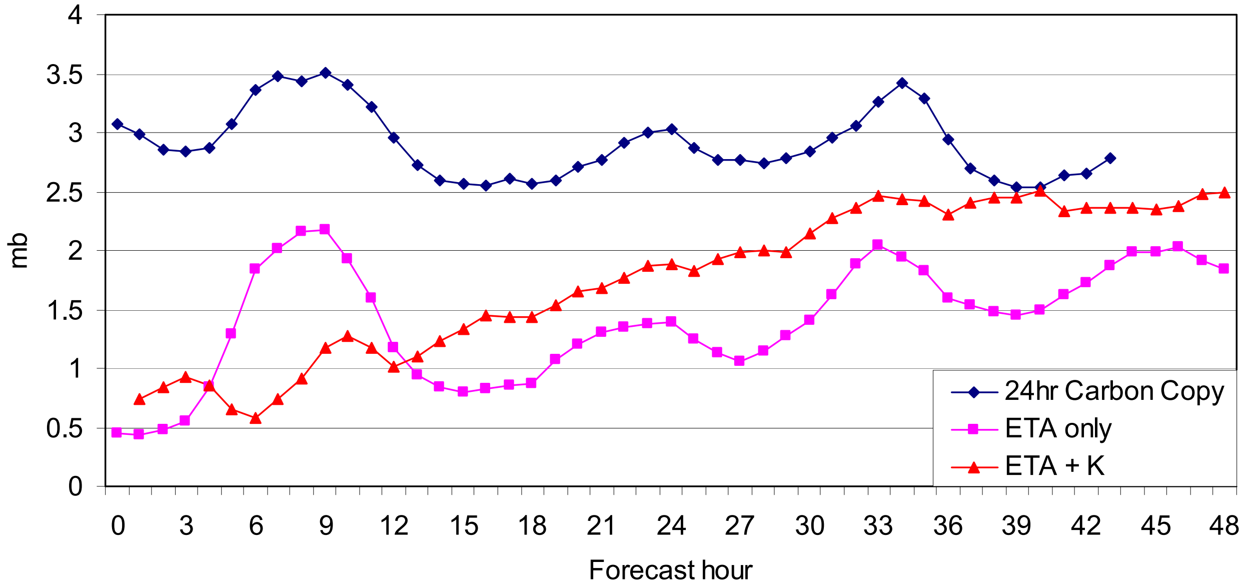

Figure 6. Mean absolute difference between observed and forecasted pressure for three forecasting methods.

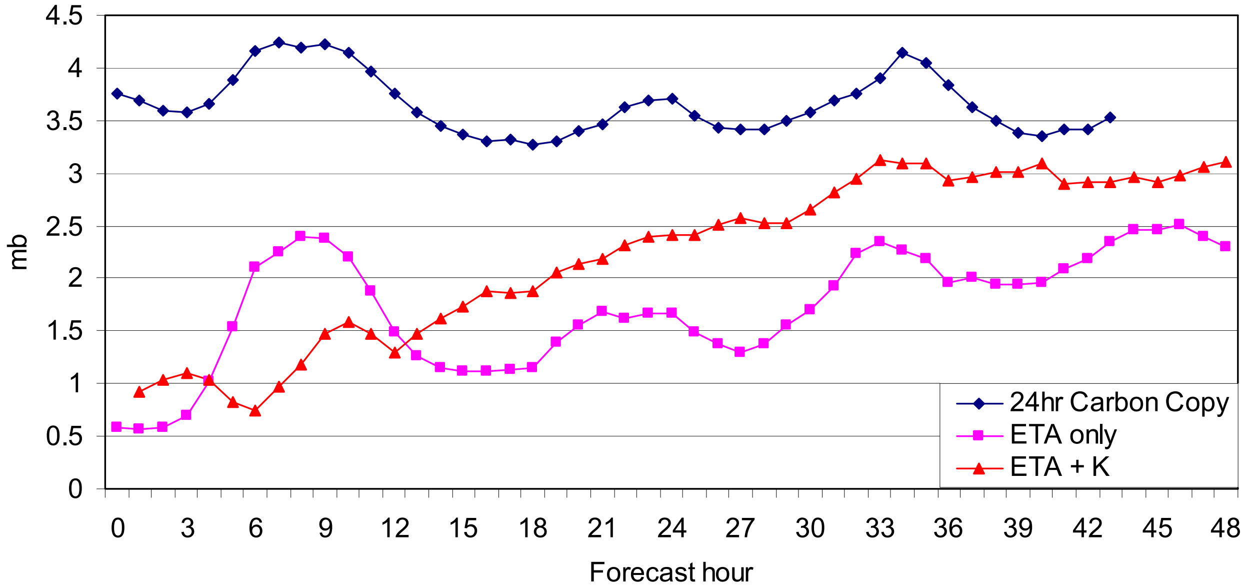

Figure 7. Root mean square difference between observed and forecasted pressure for three forecasting methods.

Figure 8 shows that this accuracy is sufficient for the detection and forecasting of low pressure events. During the month of October, 2003 there were five low pressure events of different intensities. It is clear from the plot that these events were accompanied by pressure drops of 5mb or more over 24-48 hours. If pressure is being forecasted with an accuracy of about 2mb, then these events can be accurately forecasted.

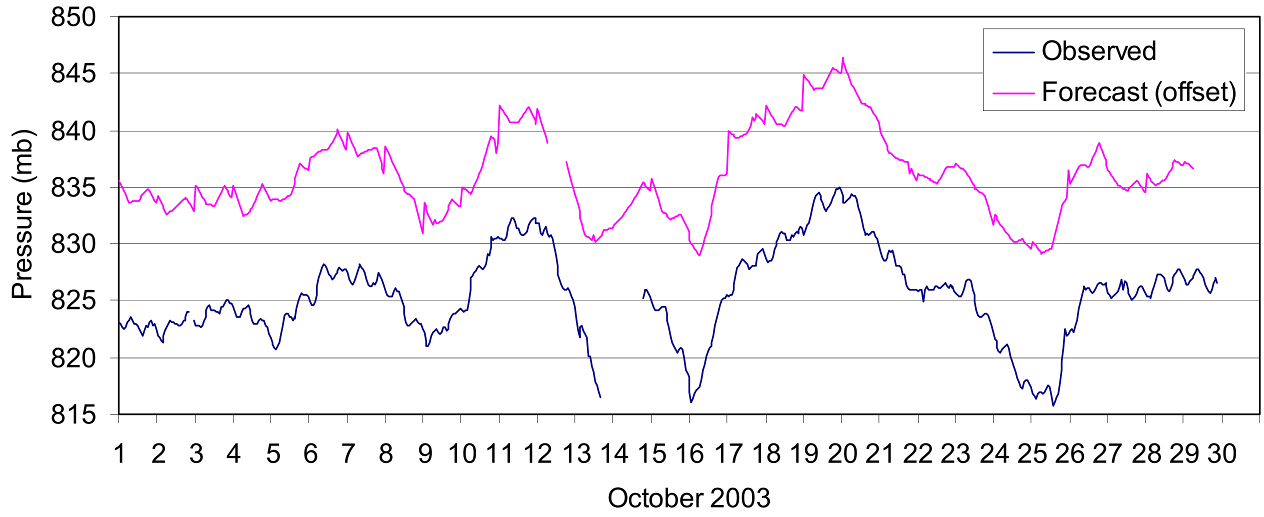

Figure 8. Forecasted and observed pressure for the month of October, 2003 (Forecast curve offset).

4.3 Relative humidity

The forecast accuracy for relative humidity is shown in Figures 9 and 10. A pattern similar to that of the other parameters is observed with the forecast based on the Eta model performing best overall with the additional use of the Kalman filter improving the forecast for a few hours after initialization. The difference between observed and forecasted relative humidity is about 20% with the best accuracy achieved around sunrise and sunset. The forecasting of relative humidity relates to providing a warning for the possibility of condensation on surfaces inside the telescope dome. Depending on the nature and temperature of the surfaces condensation will start occurring when the relative humidity is between 80% and 100%. While some false alarms may results issuing a warning based on the forecasted relative humidity, it can be seen that the relative humidity forecast is sufficiently accurate to be of value to SALT operations.

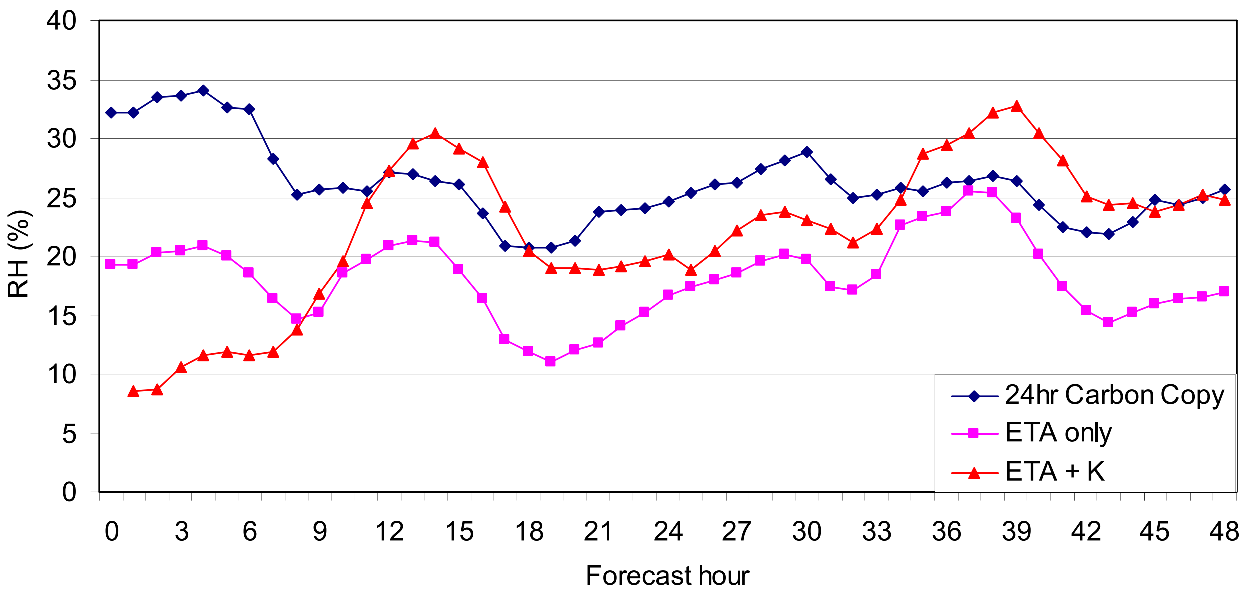

Figure 9. Mean absolute difference between observed and forecasted relative humidity for three forecasting methods.

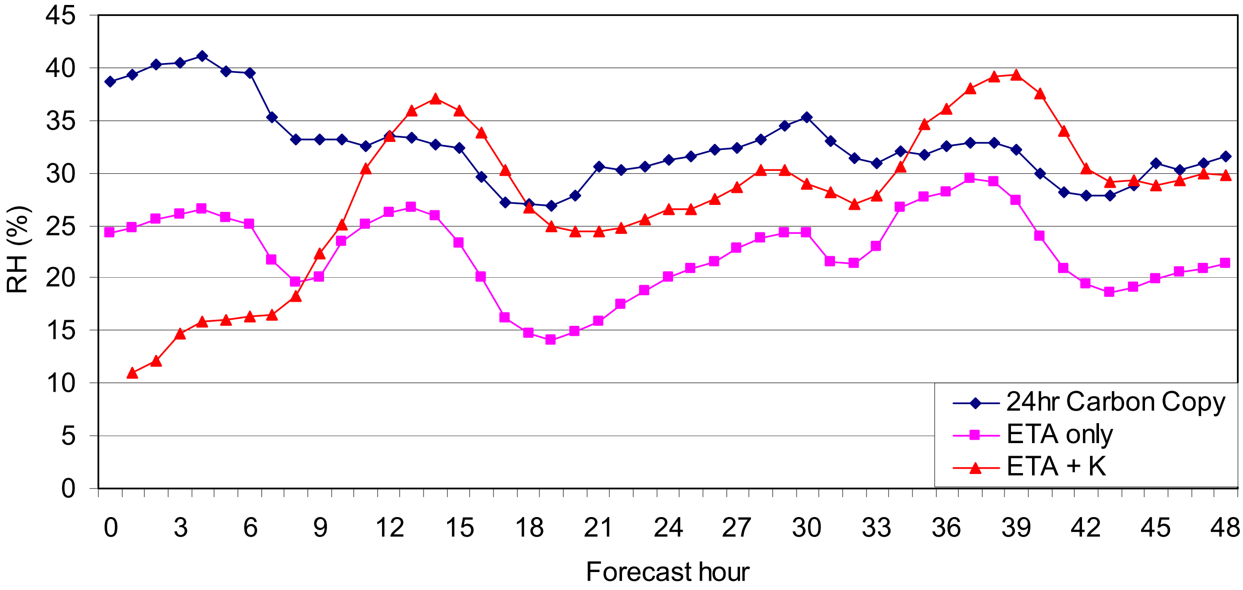

Figure 10. Root mean square difference between observed and forecasted relative humidity for three forecasting methods.

5. Future work

The following items remain to be done as part of phase 1:

(i) Evaluation of forecast accuracy for wind speed and wind direction

This is a straightforward evaluation of forecast accuracy as has been done for temperature, pressure and relative humidity in section 4.

(ii) Improved forecasting of temperature (diurnal cycle)

In this regard the goal will be to improve the accuracy of daytime high (and night-time low) temperature forecasts by incorporating information on the daily temperature cycle near the ground into the forecast programme. It was originally hoped that the application of a Kalman filter to the surface observations would accomplish this. However, the Kalman filter approach has proven to be of limited value. This approach will be given some further investigation to see if the filter can be trained or used differently in order to accomplish the desired result. If this does not prove fruitful, application of the additional Eta model data received since 15 December, 2003 will be considered. These are forecasts of surface parameters as predicted by the Eta model. Although the topography as used in the model has Sutherland Observatory at a significantly lower altitude than it actually is, the forecasts may nevertheless be of value after compensating for altitude differences. If this is unsuccessful, the possibility of using the observed data in the days prior to the forecast period in some manner other than the Kalman filter approach will be examined.