generating financial savings and, secondly, by reducing some of the pressure placed on the station's energy systems during the summer months.

It was calculated that under ideal assumptions the snow smelter would consume approximately 820 kWh daily while creating fresh water during the takeover period (when base population totals approximately 80 people). However, as shown later (in section 4.3.1), if heat losses and the snow smelter PLC logic are accounted for then the actual value is most likely more than double this amount. The consequent load on the generators required for the snow smelter is therefore on average 34 to 68 kW, with peaks that could reach up to 94 kW during the day.

The investigation described in section 3.3.1 revealed that the electrical mini-grid was characterised by large daily demand fluctuations, making it unreasonable to use an average daily load profile as a method of approximating demand during the summer period. It is important to account for the high load-profile variability when matching renewable energy systems with energy storage devices to the demand of the station. From this study the base load of SANAE IV was calculated to be 60 kW, and thus a PV system with a rated power smaller than this size was investigated (viz. a 40 kW system).

Here again emphasis was placed on the suggestion that was made in section 3.2.3 to improve the working computer simulation model of all the energy systems at the station. This would result in a number of benefits, but particularly it would help to better understand the effect that any changes will have on the station by accounting for the complex interaction of all existing systems in a way that simple calculations cannot. Furthermore, it would also make the identification of savings opportunities at the station much easier.

In section 3.2.4 it was recommended that additional methods of supplying fresh air to the plant-room should be investigated. Any added contribution of fresh air to the room would noticeably improve the working conditions during the summer. Attention was also given to some of the difficulties involved with PLC control (c.f. section 3.2.5) and heat losses to the environment (c.f. section 3.3). All of these areas justify efforts to improve the current status of the energy system.

In chapter 4 factors related to determining suitable PV and solar thermal collectors for the conditions in Antarctica were investigated. Although the purchase of photovoltaic panels in South Africa poses no problems for the implementation of a solar energy system at SANAE IV it was more difficult to find suitable locally manufactured solar thermal devices. By far the least complicated of these thermal systems is the flat-plate collector, a choice supported by considering the low ambient temperatures, high fractions of diffuse radiation and the collector tracker device reliability for instance (refer to section 4.3.1).

For the PV system some difficulty was encountered in establishing what type of inverter is most suitable for use at the base. Even though no acceptable products are currently available for purchase in South Africa, overseas markets manufacture three-phase grid-tie inverters that automatically lock onto and feed into an existing grid. Since the generators at SANAE IV output electrical energy at three-phase, 380 VAC and 50 Hz, there is no problem in obtaining an inverter that will supply electrical energy at these standard values.

The performance characteristics of the PV and solar thermal collectors under typical Antarctica conditions were also investigated, as described in chapter 4. Three methods of estimating PV efficiencies were presented in section 4.2.3 and subsequently summarised in table 4.6. The results indicate that total systems' efficiencies of PV systems should average approximately 14 % during the year, collecting approximately 200 kWh/m^2.year. In comparison, the average efficiency of the recommended solar thermal collector was calculated as 29 %, or 420 kWh/m^2.year. Results for the solar thermal systems are presented in table 4.9 and appendix D.7.

It was established in chapter 5 that a 40 kW PV system could save as much as 9 958 litres of fuel annually, and that during the same amount of time a solar thermal system (with 72 collector panels) supplementing the snow smelter could save 12 245 litres of fuel. The solar thermal collector system required a lower capital expense, thus it is not surprising that of these two options the latter is also financially more secure. Maintenance and installation of the solar thermal system requires slightly more substantial efforts, yet such efforts are still considered very reasonable within the scope of work that is required to be completed by the summer takeover maintenance crew.

The payback period for the thermal collector system was estimated at six years under the standard investment assumptions, although under more favourable conditions (high fuel price escalation rates and a lower MARR) this amount of time could be reduced to a five-year horizon. The system, which would realise an IRR of 25%, and a NPV of R 2 148 811 after 25 years, is therefore an attractive investment. The PV system, on the other hand, would only be able to break even towards the end of the project lifetime, although under the more ideal conditions of high fuel price escalation rates, lower MARRs, low attractiveness of other investment opportunities and a stronger emphasis on environmental considerations a breakeven point could potentially be realised within 13-16 years.

It should be noted, however, that a PV system is capable of reducing the size of peak electrical loads on the generators while a solar thermal device is only able to shorten the length of these peaks. Each system must be evaluated on its own merits, and each presents its own unique opportunities.

It is clear that there is ample scope for the utilisation of solar energy at South Africa's SANAE IV station in Antarctica. The suggested solar energy systems present good opportunities for reducing station load and improving living conditions during the summer, and with the proper implementation the initial capital investment can be recovered within the project lifetime (PV only towards the end of the project lifetime, and solar thermal more certainly within six years). Although these solar energy systems may seem large, it should be remembered that they could be scaled to smaller versions of those suggested, and that under these conditions they would most likely recover their capital investment in a similar period of time to that identified here.

It is recommended that an assessment of available funds be made within DEAT in order to establish what financial resources are available for the future implementation of a renewable energy system at SANAE IV. Once it has been established under what conditions these resources could be used (i.e. lending rates and available amount) a refinement of the above assessment may be performed in order to re-assess the economic implications of such a decision if necessary. Over and above the direct savings and improvements which could be realised by installing solar energy systems at SANAE IV, the increased global awareness of environmental change and greenhouse gasses should motivate a careful consideration of the benefits that renewable energy systems have to offer SANAP.

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Appendix A: Additional Information to Introduction

A.1 Additional Information

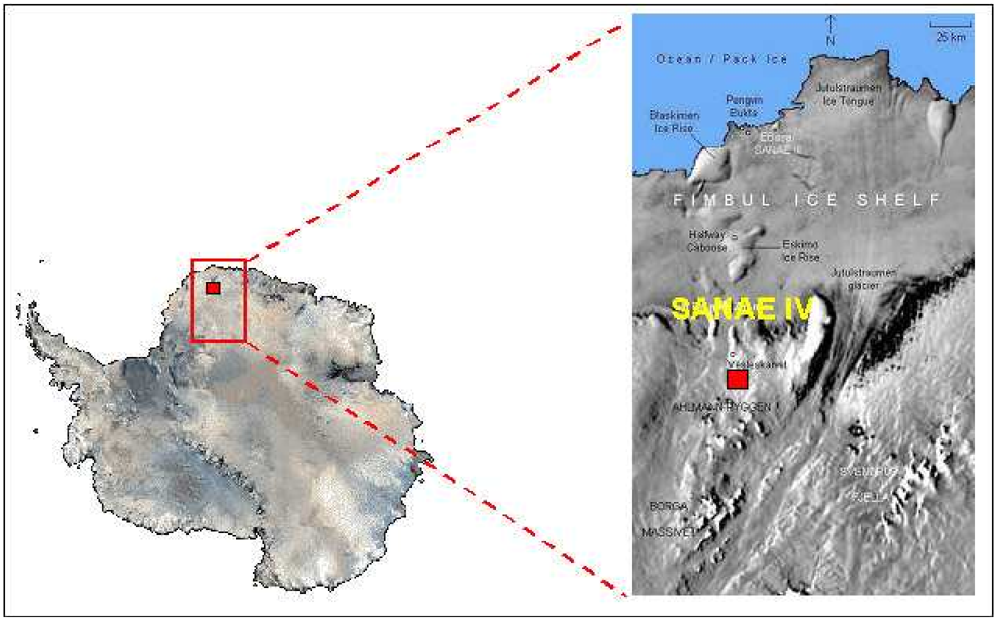

Figure A.1: SANAE IV in Queen Maud Land, Antarctica (Theodora Maps, 2005)

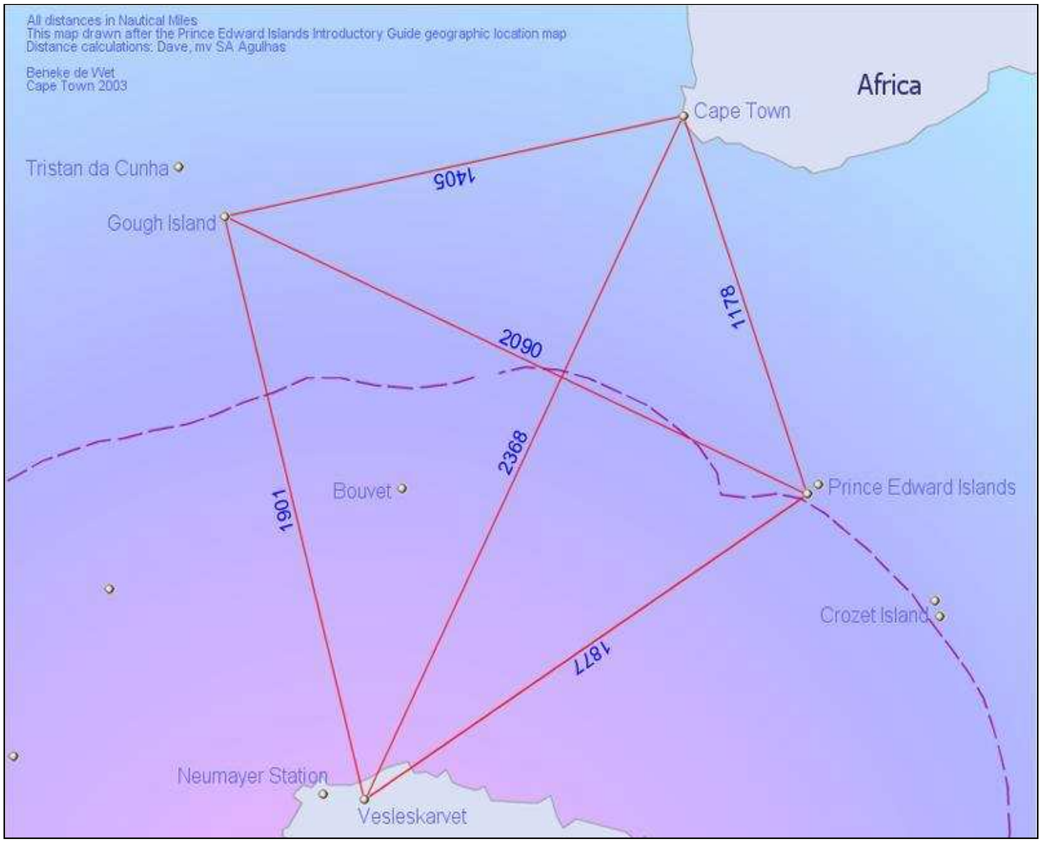

Figure A.2: SANAE IV, distances in Nautical Miles (de Wet, 2005)

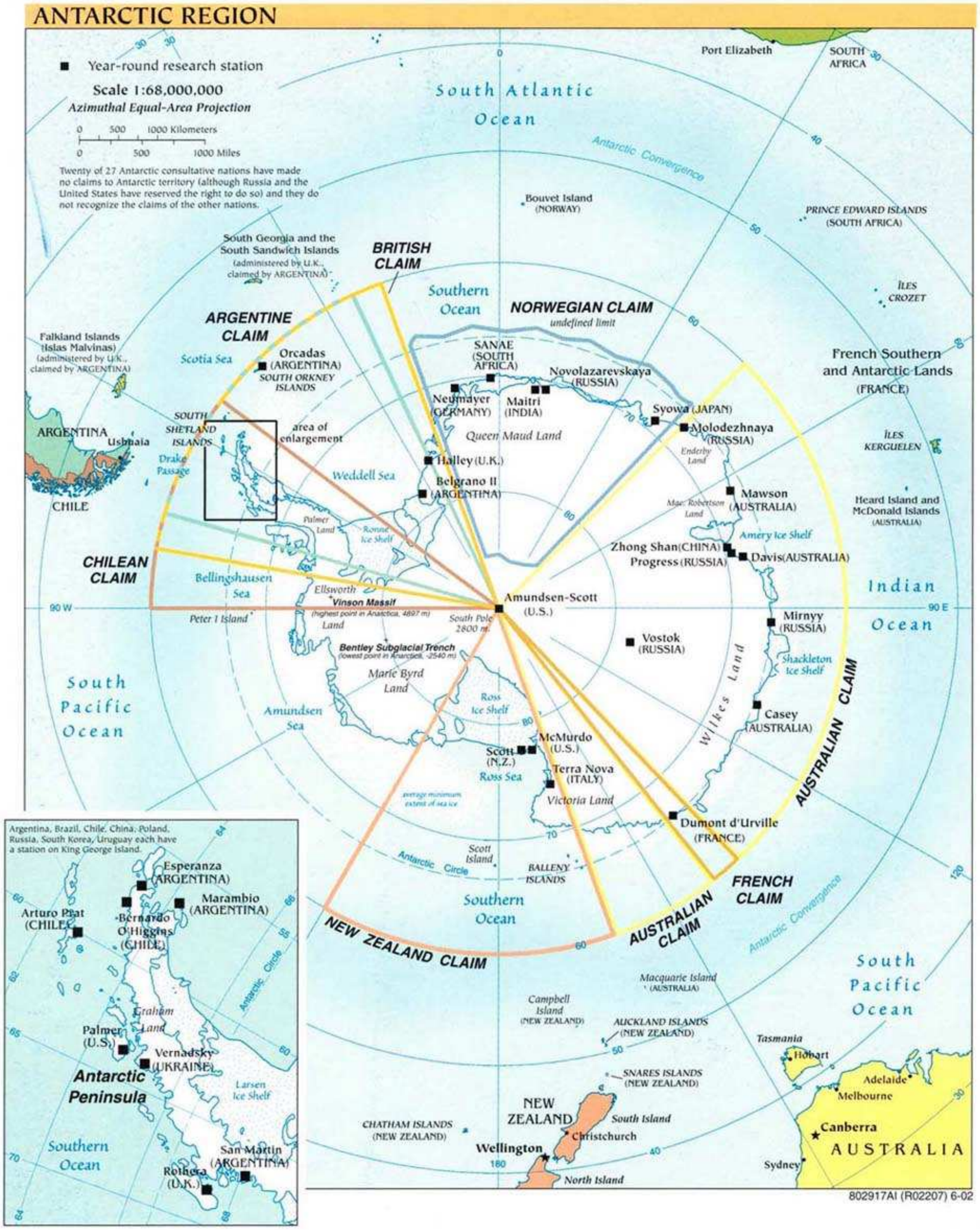

Figure A.3: Territorial claims and overwintering stations (Perry-Castañeda, 2005)

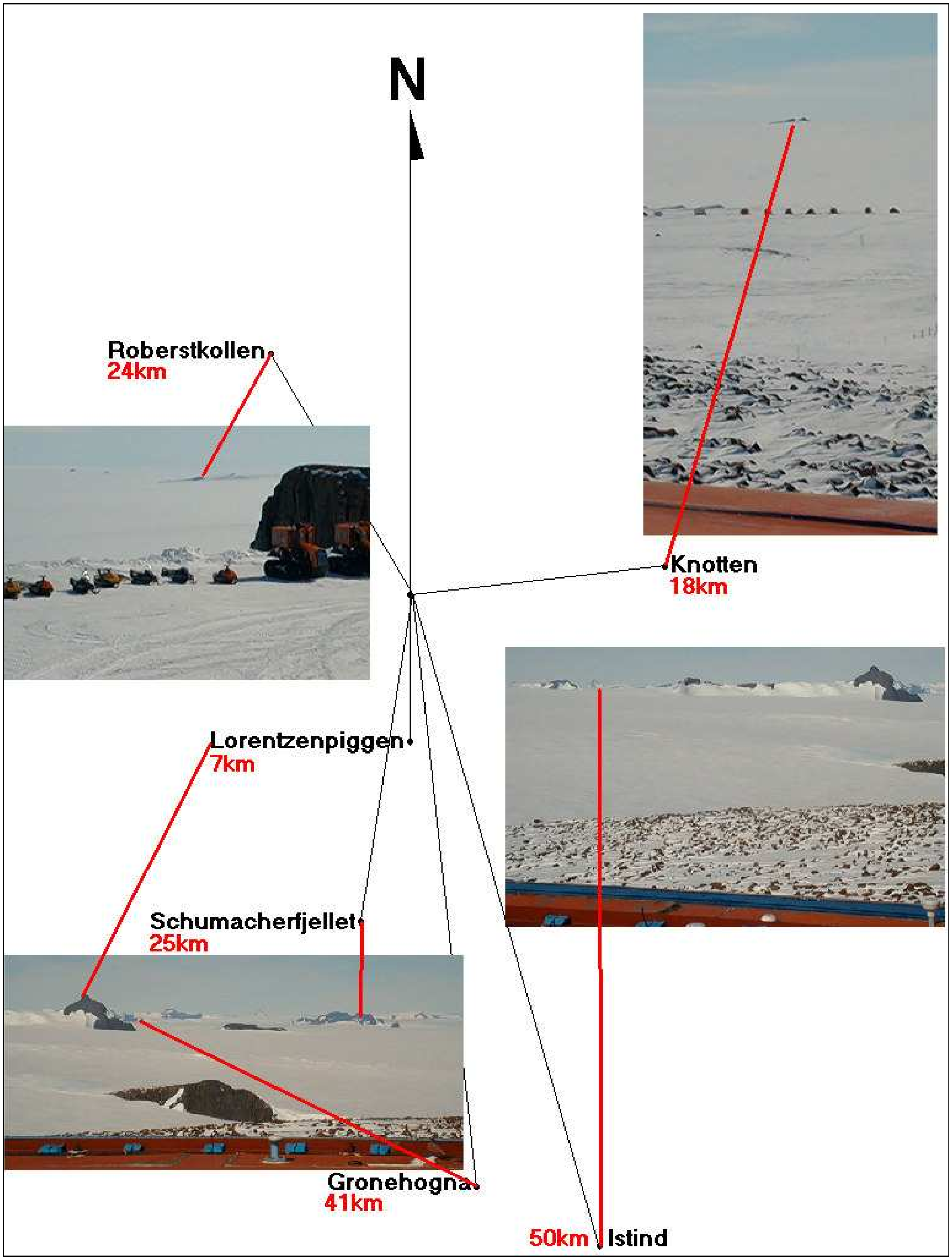

Fig A.4: View from SANAE IV (SANAE IV database, 2005)

Table A.1: Dimensions of SANAE IV

DIMENSION	UNIT	VALUE
BLOCK A		
Length of block	[m]	44.7
Width of block	[m]	12.3
Height of block	[m]	6.5
Area of roof	[m^2]	550.3
Area of sidewalls	[m^2]	707.2
Area of floor	[m^2]	550.3
BLOCK B		
Length of block	[m]	44.7
Width of block	[m]	14.2
Height of block	[m]	6.5
Area of roof	[m^2]	662.0
Area of sidewalls	[m^2]	707.8
Area of floor	[m^2]	662.0
BLOCK C		
Length of block	[m]	44.7
Width of block	[m]	15.3
Height of block	[m]	7.1
Area of roof	[m^2]	682.1
Area of sidewalls	[m^2]	816.5
Area of floor	[m^2]	682.1
CONNECTING BLOCKS		
Length of block	[m]	44.7
Width of block	[m]	12.3
Height of block	[m]	6.5
Area of roof	[m^2]	550.3
Area of sidewalls	[m^2]	707.2
Area of floor	[m^2]	550.3

A.2 Excerpt From the Antarctic Treaty of 1959 (SCAR, 2005)

"The Governments of Argentina, Australia, Belgium, Chile, the French Republic, Japan, New Zealand, Norway, the Union of South Africa, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland, and the United States of America,

Recognizing that it is in the interest of all mankind that Antarctica shall continue for ever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Acknowledging the substantial contributions to scientific knowledge resulting from international cooperation in scientific investigation in Antarctica;

Convinced that the establishment of a firm foundation for the continuation and development of such cooperation on the basis of freedom of scientific investigation in Antarctica as applied during the International Geophysical Year accords with the interests of science and the progress of all mankind;

Convinced also that a treaty ensuring the use of Antarctica for peaceful purposes only and the continuance of international harmony in Antarctica will further the purposes and principles embodied in the Charter of the United Nations;

Have agreed as follows:

Article I

1. *Antarctica shall be used for peaceful purposes only. There shall be prohibited, inter alia , any measure of a military nature, such as the establishment of military bases and fortifications, the carrying out of military manoeuvres, as well as the testing of any type of weapon.*

2. *The present Treaty shall not prevent the use of military personnel or equipment for scientific research or for any other peaceful purpose.*

Article II

Freedom of scientific investigation in Antarctica and cooperation toward that end, as applied during the International Geophysical Year, shall continue, subject to the provisions of the present Treaty.

Article III

***1.** In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that, to the greatest extent feasible and practicable:*

***a.** information regarding plans for scientific programs in Antarctica shall be exchanged to permit maximum economy of and efficiency of operations;*

***b.** scientific personnel shall be exchanged in Antarctica between expeditions and stations;*

***c.** scientific observations and results from Antarctica shall be exchanged and made freely available."*

A.3 Excerpt From the Protocol on Environmental Protection to the Antarctic Treaty of 1991 (Madrid Protocol, 1991)

"The States Parties to this Protocol to the Antarctic Treaty, hereinafter referred to as the Parties,

Convinced of the need to enhance the protection of the Antarctic environment and dependent and associated ecosystems;

Convinced of the need to strengthen the Antarctic Treaty system so as to ensure that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Bearing in mind the special legal and political status of Antarctica and the special responsibility of the Antarctic Treaty Consultative Parties to ensure that all activities in Antarctica are consistent with the purposes and principals of the Antarctic Treaty;

Recalling the designation of Antarctica as a Special Conservation Area and other measures adopted under the Antarctic Treaty system to protect the Antarctic environment and dependent and associated ecosystems;

Acknowledging further the unique opportunities Antarctica offers for scientific monitoring of and research on processes of global as well as regional importance;

Reaffirming the conservation principles of the Convention on the Conservation of Antarctic Marine Living Resources;

Convinced that the development of a Comprehensive regime for the protection of the Antarctic environment and dependent and associated ecosystems is in the interest of mankind as a whole;

Desiring to supplement the Antarctic Treaty to this end;

Have agreed as follows:

Article 2

Objective and Designation

The Parties commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and science."

Appendix B: Radiation Calculations

B.1 Predicted Available Average Radiation at SANAE IV

The following equations have been derived by increasing radiation levels suggested by SSE (2005) with 20 %, as explained in sections 2.3.3 and 2.4.

For January (where x is any number from 0 to 24):

$$G = -0.0003187 \cdot x^6 + 0.024072 \cdot x^5 - 0.64063 \cdot x^4 + 6.8013 \cdot x^3 - 22.662 \cdot x^2 + 33.863 \cdot x + 6.5175 \tag*{B.1}$$

$$Gd = -0.0001608 \cdot x^6 + 0.012169 \cdot x^5 - 0.32434 \cdot x^4 + 3.4278 \cdot x^3 - 11.02 \cdot x^2 + 16.759 \cdot x + 11.998 \tag*{B.2}$$

For February (where x is any number from 3.493 to 21.360):

$$G = -0.0012182 \cdot x^6 + 0.090864 \cdot x^5 - 2.5999 \cdot x^4 + 35.673 \cdot x^3 - 245.63 \cdot x^2 + 866.61 \cdot x - 1219.3 \tag*{B.3}$$

$$Gd = -0.0007333 \cdot x^6 + 0.054576 \cdot x^5 - 1.5697 \cdot x^4 + 21.958 \cdot x^3 - 158.09 \cdot x^2 + 597.99 \cdot x - 899.57 \tag*{B.4}$$

For March (where x is any number from 5.860 to 18.760):

$$G = -0.0025561 \cdot x^5 + 0.25082 \cdot x^4 - 8.521 \cdot x^3 + 114.08 \cdot x^2 - 640.82 \cdot x + 1230.9 \tag*{B.5}$$

$$Gd = -0.0012648 \cdot x^5 + 0.10078 \cdot x^4 - 2.9637 \cdot x^3 + 36.676 \cdot x^2 - 163.52 \cdot x + 193.12 \tag*{B.6}$$

For April (where x is any number from 8.193 to 16.193):

$$G = -0.0026532 \cdot x^5 + 0.2618 \cdot x^4 - 8.9646 \cdot x^3 + 132.14 \cdot x^2 - 826.19 \cdot x + 1748.4 \tag*{B.7}$$

$$Gd = -0.0022056 \cdot x^5 + 0.10044 \cdot x^4 - 1.6247 \cdot x^3 + 5.1313 \cdot x^2 + 115.6 \cdot x - 768.2 \tag*{B.8}$$

For May (where x is any number from 10.590 to 13.657):

$$G = -8.2884 \cdot 10^{-14} x^4 + 4.0637 \cdot 10^{-12} \cdot x^3 - 2.483 \cdot x^2 + 60.204 \cdot x - 359.08 \tag*{B.9}$$

$$Gd = -0.0020699 \cdot x^4 + 0.1488 \cdot x^3 - 5.3644 \cdot x^2 + 79.098 \cdot x - 386.72 \tag*{B.10}$$

For June and July (where x is any number from 11.999 to 12.001):

$$G = 0 \tag{B.11}$$

$$Gd = 0 \tag{B.12}$$

For August (where x is any number from 8.867 to 15.667):

$$G = 2.3785 \cdot 10^{-15} \cdot x^4 - 1.5383 \cdot 10^{-13} \cdot x^3 - 3.4373 \cdot x^2 + 84.331 \cdot x - 477.51 \tag{B.13}$$

$$Gd = -0.063729 \cdot x^4 + 3.1409 \cdot x^3 - 59.386 \cdot x^2 + 509.44 \cdot x - 1643.5 \tag{B.14}$$

For September (where x is any number from 6.5582 to 17.665):

$$G = -0.0014105 \cdot x^5 + 0.26263 \cdot x^4 - 10.501 \cdot x^3 + 162.37 \cdot x^2 - 1030.1 \cdot x + 2269.8 \tag{B.15}$$

$$Gd = 0.06291 \cdot x^4 - 2.9828 \cdot x^3 + 46.624 \cdot x^2 - 265.9 \cdot x + 465.31 \tag{B.16}$$

For October (where x is any number from 4.005 to 20.100):

$$G = -0.0015866 \cdot x^6 + 0.11482 \cdot x^5 - 3.2308 \cdot x^4 + 44.536 \cdot x^3 - 317.69 \cdot x^2 + 1181.3 \cdot x - 1785.9 \tag{B.17}$$

$$Gd = -0.0008765 \cdot x^6 + 0.06435 \cdot x^5 - 1.8296 \cdot x^4 + 25.799 \cdot x^3 - 191.5 \cdot x^2 + 751.82 \cdot x - 1194.3 \tag{B.18}$$

For November (where x is any number from 0 to 24):

$$G = -0.00049941 \cdot x^6 + 0.035343 \cdot x^5 - 0.88544 \cdot x^4 + 8.9745 \cdot x^3 - 29.957 \cdot x^2 + 39.632 \cdot x + 4.4457 \tag{B.19}$$

$$Gd = -0.00025896 \cdot x^6 + 0.018308 \cdot x^5 - 0.45638 \cdot x^4 + 4.5441 \cdot x^3 - 14.133 \cdot x^2 + 17.913 \cdot x + 7.9901 \tag{B.20}$$

For December (where x is any number from 0 to 24):

$$G = -1.6487 \cdot 10^{-8} \cdot x^{10} + 1.9982 \cdot 10^{-6} \cdot x^9 - 9.8769 \cdot 10^{-5} \cdot x^8 + 0.0025415 \cdot x^7 - \ldots$$

$$\ldots 0.035956 \cdot x^6 + 0.27337 \cdot x^5 - 1.094 \cdot x^4 + 3.0168 \cdot x^3 - 4.9394 \cdot x^2 + 25.783 \cdot x + 29.969 \tag{B.21}$$

$$Gd = -3.8755 \cdot 10^{-9} \cdot x^{10} + 5.001 \cdot 10^{-7} \cdot x^9 - 2.5358 \cdot 10^{-5} \cdot x^8 + 0.00063774 \cdot x^7 - \ldots$$

$$\ldots 0.0080792 \cdot x^6 + 0.043821 \cdot x^5 - 0.049655 \cdot x^4 + 0.21121 \cdot x^3 - 1.6514 \cdot x^2 + 16.667 \cdot x + 25.387 \tag{B.22}$$

B.2 MATLAB V6.1 Programmes Used to Calculate Insolation and Radiation at SANAE IV on a Tilted Surface

B.2.1 Programme used to calculate Insolation at SANAE IV on a tilted surface

```
%%------------------------------------------------------------------------------------------------------------------------%%
%%  PROGRAMME TO ESTIMATE INSOLATION ON A TILTED PLANE AT SANAE IV            %%
%%------------------------------------------------------------------------------------------------------------------------%%
%This programme provides the basic code for calculating what happens when a solar collecting surface
%at SANAE IV is tilted away from the horizontal using isotropic and anisotropic sky conditions.
%The algorithm can be found in Duffie and Beckman (1991, pg.109 and onwards)

%%---------------------------------------------------------------------------%%
%%  Define all the variables                                                  %%
%%---------------------------------------------------------------------------%%
%Haverage: is the global radiation value on the horizontal surface that will be transformed to a value on a tilted surface
%Hdaverage: is the diffuse radiation value on the horizontal surface that will be transformed to a value on a tilted surface
%day: is any day of that month under consideration, where the correct day is calculated from F_DayOfTheYear.m (Duffie and Beckman, 1991,
pg 14)
%roug: is the ground reflectivity (high due to snow cover)
%gam: is the surface azimuth angle (where 0=pointing South and 180=pointing North)
%phi: is the latitude of SANAE IV
%month: is that month of the year under consideration (1=January)
%Angle: is the collector tilt angle
%n: is the correct day is calculated from F_DayOfTheYear.m (Duffie and Beckman, 1991, pg 14)
%decl: is the earth's declination from the solar plane on the given day
%thetazd: is the zenith angle of the sun in degrees (Duffie and Beckman, 1991, pg. 13)
%gammaS: is the solar azimuth angle in degrees (Duffie and Beckman, 1991, pg. 13)
%omegaS: is the sunset hour angle in degrees
%w: is the hour angle in degrees

%%----------------------------------------------------------------------------------%%
%%  Preliminary calculations (used in all sub-portions of code)          %%
%%----------------------------------------------------------------------------------%%
close all
clear all
clc

%Estimated monthly-average daily values for Januray that will be used to calculate what the value on the
%tilted plane is. See appendix B1.
Haverage=[7.3 3.98 1.78 0.60 0.01 0.00 0.00 0.15 1.28 3.25 5.17 6.48]*1000*3600;   %In J/m^2
Hdaverage=[4.36 1.64 0.84 0.21 0 0 0 0 0.54 1.27 2.13 2.66]*1000*3600;            %In J/m^2
day=17;
month=1;

        %%------------------------------------------------------------------------------------------------------------------------%%
        %%                                                                                                                        %%
        %%    HOURLY-TOTAL ALGORITHMS OF ISOTROPIC AND ANISOTROPIC CONDITIONS        %%
        %%                                                                                                                        %%
        %%------------------------------------------------------------------------------------------------------------------------%%

%%-------------------------------------------------------------------------------------------%%
%%  Calculate the 3Hrly diffuse radiation using the Neumeyer 5-yr averages %%
%%-------------------------------------------------------------------------------------------%%
%Define all the neacessary initial and input conditions below
datenumber=datenum([2005,month,day,0,0,0]);
Beta=0:10:140;
dt=1/3600;        %This is a VERY IMPORTANT parameter in the logic that follows. The timestep is exactly a second long, therefore...
             %...when integrating W/m^2 no factor has to be applied and the SUM function can simply be used

%Determine the diffuse radiation for every hour of the day...
x1=0:1/3600:0.5;
[G,Gd,x]=F_MonthlyProfiles(month,x1);
for j=1:23;
   x1=j-0.5:1/3600:j+0.5;
   [G,Gd,x]=F_MonthlyProfiles(month,x1);
   I(j+1)=sum(G);
   Id(j+1)=sum(Gd);
end
```

```
%%------------------------------------------------------------------------------%%
%%  For the anisotropic sky conditions (Duffie pg.99)                          %%
%%------------------------------------------------------------------------------%%
%Following is code that illustrates the use of the Perez et al. model
s=1;
roug=[0.1:0.7:1];
for R=roug          %roug;          %Various reflectances are investigated
    t=1;
    for Bet=Beta    %Beta    %And various tilt angles are investigated
        for j=0:1:23
            q=datenum([2005,month,day,j,0,0]);
            if (Id(j+1)>0)
                [It(j+1),Idt(j+1),Ibt(j+1)]=F_TiltANISOSKY(q,Bet,I(j+1),Id(j+1),R,180);   %Assumes isotropic-sky conditions
            else
                It(j+1)=0; Idt(j+1)=0; Ibt(j+1)=0;
            end
        end
        Htilt(t,s)=sum(It);
        Htiltd(t,s)=sum(Idt);
        Hbeam(t,s)=sum(Ibt);
        t=t+1;
    end
    s=s+1;
end
%Also plot the results
Htilt=Htilt/1e6;
Htiltd=Htiltd/1e6;
Hbeam=Hbeam/1e6;

figure(100)
hold on
for i=1:length(roug)
    %Plot the total insolation
    plot(Beta,Htilt(:,i))
    %Plot the beam radiation
    % plot(Beta,Hbeam(:,i),'r-')
    %Plot the diffuse insolation
    % plot(Beta,Htiltd(:,i),'k-')
end
plot(Beta,Htilt(:,1))
grid on
xlabel('Slope of Collector Surface {\beta}'), ylabel('Insolation [MJ/m^2]')
%axis([0 Beta(end) 0 35])

%Find the maximums of the global horisontla radiation series'
for i=1:length(Htilt(1,:))
    [maxesR,maxesC]=max(Htilt(:,i));
    [maxesRb,maxesCb]=max(Hbeam(:,i));
    [maxesRd,maxesCd]=max(Htiltd(:,i));
    % plot(Beta(maxesC),maxesR,'rv',Beta(maxesCb),maxesRb,'rv',Beta(maxesCd),maxesRd,'rv')
end
hold off

%For the highest ground reflectivity under investigation...
disp(['the avialable global insolation on the horizontal surface is: '])
disp([num2str(Htilt(1,1)*1000/3600), ' kWh'])

disp(['the avialable beam insolation on the horizontal surface is: '])
disp([num2str(Hbeam(1,1)*1000/3600), ' kWh'])

disp(['the optimum global insolation tilt angle is: '])
disp([num2str(Beta(maxesC)), ' degrees'])

disp(['the optimum beam tilt angle is: '])
disp([num2str(Beta(maxesCb)), ' degrees'])

disp(['the avialable global insolation on the tilted surface is: '])
disp([num2str(maxesR*1000/3600), ' kWh'])

disp(['the avialable beam insolation on the tilted surface is: '])
disp([num2str(maxesRb*1000/3600), ' kWh'])
```

```
%%--------------------------------------------------------------------------%%
%%  For the isotropic sky conditions (Duffie pg.94)                         %%
%%--------------------------------------------------------------------------%%
%Now calculate the total insolation on a tilted panel with the relevant hourly I and Id values
s=1;
roug=0.5:0.5:1;
for R=roug;       %Various reflectances are investigated
   t=1;
   for Bet=Beta   %And various tilt angles are investigated
      for j=0:1:23
         q=datenum([2005,month,day,j,0,0]);
         [It(j+1),Idt(j+1)]=F_TiltISOSKY(q,Bet,I(j+1),Id(j+1),R,180);   %Assumes isotropic-sky conditions
      end
      Htilt(t,s)=sum(It);
      Htiltd(t,s)=sum(Idt);
      t=t+1;
   end
   s=s+1;
end
%Also plot the results
Htilt=Htilt/1e6;
Htiltd=Htiltd/1e6;
figure(200)
grid on
for i=1:length(roug)
   hold on
   plot(Beta,Htilt(:,i),'b-')
   hold off
end
xlabel('Slope of Collector Surface {\beta}'), ylabel('Insolation [MJ/m^2]')
axis([0 Beta(end) 0 35])
%axis([Beta(1) Beta(end) 0 35]);
```

B.2.2 Programme used to calculate Radiation at SANAE IV on a tilted surface

```
%%------------------------------------------------------------------------------------------------------------------------------------------%%
%%  PROGRAMME TO COMPUTE  INSTANTANEOUS RADIATION AT SANAE IV ON A TILTED PLANE                                                             %%
%%------------------------------------------------------------------------------------------------------------------------------------------%%
%This programme provides the basic code for calculating what happens when a solar collecting surface
%at SANAE IV that is tilted away from the horizontal using isotropic and anisotropic sky conditions.
%The algorithm can be found in Duffie and Beckman (1991, pg.109 and onwards)
close all
clear all
clc

%%------------------------------------------------------------------------------%%
%%  Preliminary calculations (used in all sub-portions of code)                 %%
%%------------------------------------------------------------------------------%%
%Define all the necessary initial and input conditions below
dt=1;
A=0.840;
month=1;
day=15;
%Beta=70;
Beta=[52 63 74 84 86 86 86 88 78 69 52 48]; %Which are the optimum tilt angles of every month
gamma=180;
flag1=1; %Determines whether the Hottel clear-sky prediction is used (flag=1, only valid for January), or the measured global horizontal data
flag2=0; %Determines whether the Anisotropic (flag2=0) or isotropic conditions must be used for tilting the collector
flag3=0; %Determines whether measured data must be plotted (flag3=1)
flag4=0; %Determines whether the average radiation profiles must be used (flag4=1) instead of Hottel

      %%-------------------------------------------------------------------------------------------------------------------%%
      %%                                                                                                                   %%
      %%     INSTANTANEOUS ALGORITHMS OF ISOTROPIC AND ANISOTROPIC CONDITIONS                                               %%
      %%                                                                                                                   %%
      %%-------------------------------------------------------------------------------------------------------------------%%


if (flag1==1) & (flag4==0)     %If it is desired that the Hottel clear-sky correlation is used
```

```
    %%--------------------------------------------------------------------------------%%
    %%  Determine the clear-sky radiation on the given day                    %%
    %%--------------------------------------------------------------------------------%%
    %Hottel and Liu and Jordan clear sky models
    A0Star=0.4237-0.00821*(6-A)^2;
    A1Star=0.5055+0.00595*(6.5-A)^2;
    KStar=0.2711+0.01858*(2.5-A)^2;
    r0=0.99;
    r1=0.99;
    rk=1.02;
    a0=r0*A0Star;
    a1=r1*A1Star;
    k=rk*KStar;
    kk=0.45*KStar; %NOTE: This is a personal fit of the extinction co-efficient

    %The beam transmittance and horizontal beam radiation is calculated as...
    s=1;
    q=datenum(2005,month,day,0,0,0);    %The day of the year under investigation
    stepsize=1/24/60;
    for i=q:stepsize:q+1
        [zenithd,gammaS,b]=F_SolarAngles(i);
        n=F_DayOfTheYear(q);

        taub=a0+a1*exp(-k/cos(zenithd*pi/180));
        taubb=a0+a1*exp(-kk/cos(zenithd*pi/180)); %This is a personal fit of the extinction co-efficient
        Gon=1367*(1+0.033*cos(360*n/365*pi/180));
        Gcb(s)=Gon*taub*cos(zenithd*pi/180);
        Gcbb(s)=Gon*taubb*cos(zenithd*pi/180); %This is a personal fit of the extinction co-efficient

        taud=0.271-0.294*taub;
        Gd(s)=taud*1367*(1+0.033*cos(360*n/365*pi/180))*cos(zenithd*pi/180);

        s=s+1;
    end

    %The total horizontal radiation is defined as the sum of the clear-sky beam
    %and the clear sky diffuse
    Gtot=Gcbb+Gd; %This is a personal fit of the extinction co-efficient
    %Now make a x-axis vector for plotting that runs from 0 to 1 (a day in length)
    r=length(Gtot);
    ex=(0:1/(r-1):1)*24;
elseif (flag1==0) & (flag4==0)
    %Retrieve the measured data on the relevant day
    [M]=D_DataCompareMain(day);
    M(:,1:2:end)=M(:,1:2:end)*24;
    for i=1:length(M(:,1))
        if M(i,1)>=24
            M(i,1:2:end)=M(i,1:2:end)-24;
        end
    end
    Gtot=M(:,2);
    Gd=M(:,6);
    r=length(Gtot);
    ex=M(:,1)';
elseif flag4==1;
    ex=0:1/60*10:24;
    [Gtot,Gd,ex]=F_MonthlyProfiles(month,ex);
end

%%--------------------------------------------------------------------------%%
%%  For the isotropic sky conditions (Duffie pg.99)                    %%
%%--------------------------------------------------------------------------%%
%Following is code that illustrates the use of the Perez et al. model
s=1;
for R=0.7;          %Various reflectances are investigated
    t=1;
    for Bet=Beta(month)    %And various tilt angles are investigated
        p=1;
        for x=ex
            hourr=floor(x);
            minn=floor((x-floor(x))*60);
            secc=(x-hourr-minn/60)*3600;
            q=datenum([2005,1,day,hourr,minn,secc]);
            if flag2==0
                [Gt(p),Gdt(p),Gbt(p)]=F_TiltANISOSKY(q,Bet,Gtot(p),Gd(p),R,gamma);   %Assumes anisotropic-sky conditions
            elseif flag2==1
```

```
            [Gt(p),Gdt(p),Gbt(p)]=F_TiltISOSKY(q,Bet,Gtot(p),Gd(p),R,gamma);   %Assumes isotropic-sky conditions
         end
         p=p+1;
      end
      t=t+1;
   end
   s=s+1;
end

if flag3==1
   figure(300)
   %Plot the daily profile of the tilted surface
   hold on
   plot(M(:,1),M(:,2),'bv','markersize',3)
   plot(ex,Gt,'r.','markersize',3)
   plot(M(:,13),M(:,14),'bo','markersize',3), grid on
   %plot(M(:,1),M(:,2))
   hold off
   xlabel('Time of day (in hours from midnight)'), ylabel('Radiation [W/m^2]')
   legend('Measured global horizontal radiation','Predicted radiation at tilt angle', 'Measured radiation at tilt angle')
   axis([0 24 0 1600])

   %Caclulate the percentage difference between predicted and measured curves
   xx=0:1/3600:24;
   yy1=spline(M(:,13),M(:,14),xx);
   tot1=sum(Gt);
   yy2=spline(ex,Gt,xx);
   tot2=sum(M(:,14));
   percentage=tot2/tot1*100
else
   figure(300)
   %Plot the daily profile of the tilted surface
   hold on
   plot(ex,Gt,'r-','markersize',3)
   %plot(M(:,1),M(:,2))
   hold off
   xlabel('Time of day (in hours from midnight)'), ylabel('Radiation [W/m^2]')
   legend('Predicted radiation at tilt angle')
   axis([0 24 0 1600])
end
```

B.3 MATLAB V6.1 Functions Used in Conjunction with the Programmes in B2 to Calculate Radiation on a Tilted Surface

B.3.1 Function F_TiltANISOSKY.m

```
function [It,Idt,Ibt]=F_TiltANISOSKY(q,B,I,Id,roug,g)
%%-- Duffie and Beckman (John Wiley and Sons, Inc., 1991, pg 97)
%This programme calculates the amount of insolation incident on a tilted surface if the
%Perez et al. anisotropic sky (1988) method is used. NB - Input values are in J/m^2.

%%--------------------------------------------------------------------------%%
%%  Convert the daynumber to its component values                           %%
%%--------------------------------------------------------------------------%%
[datenumber]=F_SolarTime(q);
[y,month,day,h,mn,s]=datevec(datenumber);

%%--------------------------------------------------------------------------%%
%%  Main Programme                                                          %%
%%--------------------------------------------------------------------------%%
Ib=I-Id;
if I<=Id
   I=Id;
   Ib=0;
end

%Calculate the values required for determining Rb
phi=-71.67305556;
```

```
n=F_DayOfTheYear(datenumber);
decl=23.45*sin(pi/180*360*(284+n)/365);

%Calculate the hour angle (equals 15 degrees per hour).
[thetazd,gammaS,omegaS,w]=F_SolarAngles(datenumber);

%Convert to radians
declR=decl*pi/180;
phiR=phi*pi/180;
wR=w*pi/180;
BR=B*pi/180;
thetazR=thetazd*pi/180;
gR=g*pi/180+pi; %The "+180" is to correct for a convention that says 0=pointing South
gsR=gammaS*pi/180;

% %Calculate Rb - RETScreen method (...doesn't seem to work)
% denominator=cos(thetazR);
% gsR=asin(sin(wR)*cos(declR)/sin(thetazR));
% numerator=cos(thetazR)*cos(BR)+(1-cos(thetazR))*(1-cos(BR))*(cos(gsR-gR));
% Rb=numerator/denominator;

% %Calculate Rb - Duffie method (...works when predicting instantaneous radiation values)
% numerator=cos(phiR+BR)*cos(declR)*cos(wR)+sin(phiR+BR)*sin(declR);
% denominator=cos(thetazR);
% Rb=numerator/denominator;

%Calculate Rb - Duffie method (...works when predicting instantaneous radiation values)
numerator=cos(thetazR)*cos(BR)+sin(thetazR)*sin(BR)*cos(gsR-gR);
denominator=cos(thetazR);
Rb=numerator/denominator;

% %Calculate Rb - Duffie extended method (...works when predicting instantaneous radiation values)
% gammasd=180/pi*(atan(sin(wR)/(sin(phiR)*cos(wR)-cos(phiR)*tan(declR))));
% omegaew=180/pi*(acos(tan(declR)/tan(phiR)));
% if abs(w)<omegaew
%     C1=1;
% else
%     C1=-1;
% end
% if (phi*(phi-decl))>=0
%     C2=1;
% else
%     C2=-1;
% end
% if w>=0
%     C3=1;
% else
%     C3=-1;
% end
% if abs(tan(declR)/tan(phiR))>1
%     C1=1;
% end
% gsR=(C1*C2*gammasd+C3*((1-C1*C2)/2)*180)*pi/180;
% numerator=cos(thetazR)*cos(BR)+sin(thetazR)*sin(BR)*cos(gsR-gR);
% denominator=cos(thetazR);
% Rb=numerator/denominator;

if Rb<0
   Rb=0;
end
%Calculate the total insolation on the tilted surface
a=max([0,cos(thetazR)]);
b=max([cos(85*pi/180),cos(thetazR)]);

In=Rb*I;
epsilon=(((Id+In)/Id)+(5.535e-6)*thetazd^3)/(1+(5.535e-6)*thetazd^3);
m=1/cos(thetazR);
Ion=4.921e6*(1+0.0333*cos(pi/180*360*n/365));
delta=m*Id/Ion;

if 0<=epsilon & epsilon<1.065
   f11=-0.196; f12=1.084; f13=-0.006; f21=-0.114; f22=0.180; f23=-0.019;
elseif 1.065<=epsilon & epsilon<1.230
   f11=0.236; f12=0.519; f13=-0.180; f21=-0.011; f22=0.020; f23=-0.038;
elseif 1.230<=epsilon & epsilon<1.500
   f11=0.454; f12=0.321; f13=-0.255; f21=0.072; f22=-0.098; f23=-0.046;
```

```
elseif 1.500<=epsilon & epsilon<1.950
    f11=0.866; f12=-0.381; f13=-0.375; f21=0.203; f22=-0.403; f23=-0.049;
elseif 1.950<=epsilon & epsilon<2.800
    f11=1.026; f12=-0.711; f13=-0.426; f21=0.273; f22=-0.602; f23=-0.061;
elseif 2.800<=epsilon & epsilon<4.500
    f11=0.978; f12=-0.986; f13=-0.350; f21=0.280; f22=-0.915; f23=-0.024;
elseif 4.500<=epsilon & epsilon<6.200
    f11=0.784; f12=-0.913; f13=-0.236; f21=0.173; f22=-1.045; f23=0.065;
elseif 6.200<=epsilon
    f11=0.318; f12=-0.757; f13=0.103; f21=0.062; f22=-1.698; f23=0.236;
end

F1=max([0,(f11+f12*delta+thetazR*f13)]);
F2=f21+f22*delta+thetazR*f23;

Ibt=Ib*Rb;
It=Ib*Rb+Id*(1-F1)*((1+cos(BR))/2)+Id*F1*a/b+Id*F2*sin(BR)+I*roug*((1-cos(BR))/2);
%Idt=Id*((1-F1)*((1+cos(BR))/2)+F1*a/b+F2*sin(BR));
Idt=It-Ibt;
```

B.3.2 Function F_TiltISOSKY.m

```
function [Itot,Idt,Ibt]=F_TiltISOSKY(datenumber,B,I,Id,roug,g)
%%-- Duffie and Beckman (John Wiley and Sons, Inc., 1991, pg 94)
%This programme calculates the amount of insolation incident on a tilted surface if the
%Liu and Jordan isotropic sky (1960) method is used. NB - Input values are in J/m^2.

%%---------------------------------------------------------------------------%%
%%  Convert the daynumber to its component values                  %%
%%---------------------------------------------------------------------------%%
[datenumber]=F_SolarTime(datenumber);
[y,month,day,h,mn,s]=datevec(datenumber);

%%---------------------------------------------------------------------------%%
%%  Main Programme                                                              %%
%%---------------------------------------------------------------------------%%
Ib=I-Id;
if I<=Id
    I=Id;
    Ib=0;
end

%Calculate the values required for determining Rb
phi=-71.67305556;
n=F_DayOfTheYear(datenumber);
decl=23.45*sin(pi/180*360*(284+n)/365);

%Calculate the hour angle (equals 15 degrees per hour).
[thetazd,gammaS,omegaS,w]=F_SolarAngles(datenumber);

%Convert to radians
declR=decl*pi/180;
phiR=phi*pi/180;
wR=w*pi/180;
BR=B*pi/180;
thetazR=thetazd*pi/180;
gR=g*pi/180+pi; %The "+180" is to correct for a convention that says 0=pointing South;
gsR=gammaS*pi/180;

% %Calculate Rb - RETScreen method (...doesn't seem to work for Southern Hemisphere)
% denominator=cos(thetazR);
% gsR=asin(sin(wR)*cos(declR)/sin(thetazR));
% numerator=cos(thetazR)*cos(BR)+(1-cos(thetazR))*(1-cos(BR))*(cos(gsR-gR));
% Rb=numerator/denominator;

%Calculate Rb - Duffie method (...works when predicting instantaneous radiation values)
numerator=cos(phiR+BR)*cos(declR)*cos(wR)+sin(phiR+BR)*sin(declR);
denominator=cos(thetazR);
Rb=numerator/denominator;

% %Calculate Rb - Duffie method (...works when determining instantaneous radiation values)
% numerator=cos(thetazR)*cos(BR)+sin(thetazR)*sin(BR)*cos(gsR-gR);
% denominator=cos(thetazR);
```

```
% Rb=numerator/denominator;

% %Calculate Rb - Duffie extended method (...works when determining instantaneous radiation values)
% gammasd=180/pi*(atan(sin(wR)/(sin(phiR)*cos(wR)-cos(phiR)*tan(declR))));
% omegaew=180/pi*(acos(tan(declR)/tan(phiR)));
% if abs(w)<omegaew
%     C1=1;
% else
%     C1=-1;
% end
% if (phi*(phi-decl))>=0
%     C2=1;
% else
%     C2=-1;
% end
% if w>=0
%     C3=1;
% else
%     C3=-1;
% end
% if abs(tan(declR)/tan(phiR))>1
%     C1=1;
% end
% gsR=(C1*C2*gammasd+C3*((1-C1*C2)/2)*180)*pi/180;
% numerator=cos(thetazR)*cos(BR)+sin(thetazR)*sin(BR)*cos(gsR-gR);
% denominator=cos(thetazR);
% Rb=numerator/denominator;

if Rb<0
    Rb=0;
end
%Calculate the total insolation on the tilted surface
Ibt=Ib*Rb;
Irt=I*roug*((1-cos(BR))/2); %The reflected component
Idt=Id*((1+cos(BR))/2) + Irt;

Itot=Ibt+Idt;
```