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Mass-balance modelling of the Greenland ice sheet: a comparison of an energy-balance and a degree-day model

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ABSTRACT. A degree-day model and an energy-balance model for the Greenland ice sheet are compared. The two models are compared at a grid with 20 km spacing. Input for both models is elevation, latitude and accumulation. The models calculate the annual ablation over the entire ice sheet. Although on the whole the two models yield similar results, depending on the tuning of the models, regional discrepancies of up to 45% occur, especially for northern Greenland. The performance of the two types of model is evaluated by comparing the model results with the sparsely available (long-term) mass-balance measurements. Results show that the energy-balance model tends to predict a more accurate mass-balance gradient with elevation than does the degree-day model.

Since so little is known about the present-day climate of the ice sheet, it is more useful to consider the sensitivity of the ablation to various climate elements than to consider the actual present-day ablation. Results show that for a 1 K temperature perturbation, sea-level rise is 0.31 mm year^{-1} for the energy-balance model and 0.34 mm year^{-1} for the degree-day model. After tuning the degree-day model to a value of the ablation, equivalent to the ablation calculated by the energy-balance model, sensitivity of the degree-day model increases to 0.37 mm sea-level change per year. This means that the sensitivity of the degree-day model for a 1 K temperature perturbation is about 20% higher than the sensitivity of the energy-balance model. Another set of experiments shows that the sensitivity of the ablation is dependent on the magnitude of the temperature perturbation for the two models. Both models show an increasing sensitivity per degree for larger perturbations. The increase in the sensitivity is larger for the degree-day model than for the energy-balance model. The differences in the sensitivity are mainly concentrated in the southern parts of the ice sheet.

Experiments for the Bellagio temperature scenario, 0.3°C increase in temperature per decade, leads to sea-level rise of 4.4 cm over a period of 100 years for the energy-balance model. The degree-day model predicts for the same forcing a 5.8 cm rise which is about 32% higher than the result of the energy-balance model.

INTRODUCTION

The response of ice sheets to climate forcing is complicated and depends on the interaction between ice flow, ice temperature and bedrock adjustment. Many attempts have been made to model the dynamics of ice flow; these have ranged from simple to mathematically rigorous treatments. The success of such simulations is determined largely by the accuracy with which the mass-balance history can be reconstructed or formulated (e.g. Greuell, 1992; Wal and Oerlemans, 1995). During the last decade, several mass-balance models have been developed in order to estimate the effect of climate change. The models focus on the formulation of the ablation, which physically is determined to a large extent by the energy balance of the surface in summer (e.g. Ambach, 1963). It therefore seems advisable that in modelling ablation one should start by calculating the surface-energy budget (Oerlemans, 1993). There are, however, several reasons for choosing another approach. The use of energy-balance models in climate-change experiments is considered to be of limited value because in general no future scenarios for changes in cloudiness, cloud height, wind speed, relative humidity and other variables are available (Jóhannesson and others, 1993). A second disadvantage is that computation of the energy balance over a whole ice sheet is complicated because not much information is available away from measurement sites (Jóhannesson and others, 1993). This disadvantage can, however, be turned into an advantage because the use of various meteorological input parameters allows a more sophisticated sensitivity analysis of an ablation model. The aforementioned disadvantages, together with the long computation times required, justified the consideration of simplifications in the past.

From a statistical point of view, it can be shown that at specific sites there is a high correlation between the positive degree-days and ablation at West Greenland ice-margin locations (Braithwaite and Olesen, 1985). For this reason, ablation models have been developed based entirely on the temperature, so-called degree-day models. These models calculate the ablation based upon mean

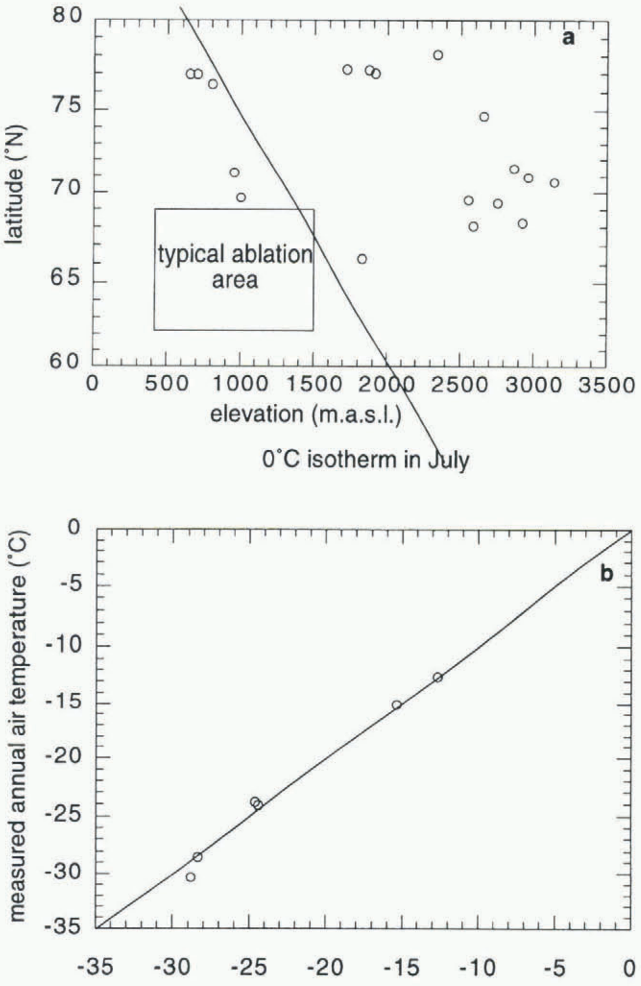

Fig. 1. All available monthly mean July temperature measurements as a function of latitude and elevation for the Greenland ice sheet (a) (Ohmura, 1987). The measured and parameterized mean annual air temperature for the Greenland ice sheet (b). The open circles show all available annual mean temperature measurements.

annual air temperature and summer air temperature. Here we follow the approach presented by Reeh (1991). An obvious problem with these models is that if the mean temperature of the warmest month is below zero no ablation occurs, whereas it is likely that there are days with ablation. This might be due to the daily cycle in the temperature as well as to random variations in the temperature or to a positive net radiation. To account for this obvious shortcoming a stochastic term is introduced, which is constant over the entire domain. It should, however, be noticed that for instance for Greenland the diurnal cycle of the temperature is about 15°C in the central parts of the ice sheet, whereas this is only 4°C near the ice margin in summer (Putnins, 1970; Broeke and others, 1994). A second simplification of reality is the constant degree-day factors for snow and ice (Huybrechts and others, 1991; Reeh, 1991; Fabre and others, 1995) representing the difference in albedo between snow and ice. In reality, albedo variations are observed from place to place as well as in the course of the season (e.g. Wal and Oerlemans, 1994).

Obviously, a degree-day model formulation and energy-balance models can be criticized on several grounds. However, the main advantage of a degree-day model is the use of the best-known meteorological parameter. To judge whether the temperature field used is reliable, we consider the applied temperature distribution for the Greenland ice sheet presented by Ohmura (1987) and digitized by Letréguilly and others (1991). Ohmura (1987) presented a new set of monthly and annual temperature maps, using all available data and reducing them to a standard period (1951–60). Reeh (1991) and Huybrechts and others (1991) presented a parameterization of these data in terms of latitude (ϕ) and elevation (h_s). Figure 1a summarizes the distribution of the ice-sheet points (18 altogether) used to validate the parameterization of the July temperature (Ohmura, 1987). This figure shows that most stations are located in central parts, higher up on the ice sheet. If we are interested in using a parameterization of the temperature to calculate the ablation, we assume the parameterization is accurate for a typical ablation area as shown in Figure 1a. Clearly, no measurements were available in the part that is the most interesting for ablation calculation. For the parameterization of the annual mean temperature, even fewer data are available than for the parameterization of the July temperature (Fig. 1b).

On the basis of this limited knowledge, one can therefore only conclude that the insight into the "best-known" meteorological parameter is very poor. In other words, at the moment the main advantage of degree-day models suffers from the main disadvantage of energy-balance models, i.e. limited insight into the input variables. This means that the choice of model to calculate the ablation is a conceptual choice rather than a firmly physically based one. Since the choice is not obvious and both methods are used nowadays, it seems worthwhile to compare them.

In this paper an attempt is made to compare and explain the nature of the observed discrepancies between a degree-day model and an energy-balance model for the Greenland ice sheet. The model results are also compared with the sparse mass-balance measurements. Given the limited insight into the present-day climate of the ice sheet, it may be more useful to consider the sensitivity of the ablation to various climate variables than the actual present-day ablation distribution. Therefore, some experiments will be presented for different climate scenarios.

ANALYSES OF THE PRESENT STATE

A few energy-balance models and degree-day models exist. To simplify a comparison, the most logical choice is to use those models which have the same level of detail in time and space. The first universal degree-day model is the one presented by Reeh (1991) and the second one is the version presented by Huybrechts and others (1991) (see Appendix). The governing equations of the two degree-day models are entirely similar but different constants are used. The two models are compared in the Appendix. Reeh (1991) used the model to calculate the ablation along a few specific profiles (61° N, 64.5° N, 69.5° N and 77° N) and compared the results with measured mass-balance elevation relationships. Huybrechts and others (1991) used the model on a grid with 20 km spacing to calculate the ablation over the entire ice

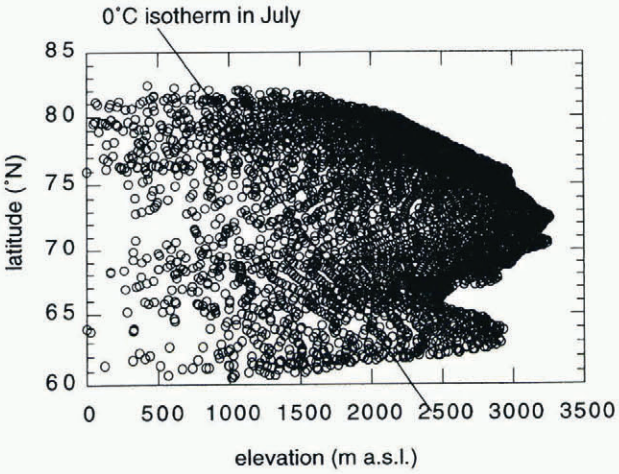

Fig. 2. Distribution of grid points over the ice sheet as a function of latitude (ϕ) *and elevation* (h). *The line gives an estimate of the 0°C isotherm in July calculated with a simple parameterization* ($h_{(T\mathrm{July}=0)} = 5960-66 \times \phi$) *presented by Reeh (1991).*

sheet. In this comparison we want to combine these two ideas. First, we are interested in the ablation over the entire ice sheet, and secondly we believe that a comparison of calculated and measured mass-balance profiles is the best method of validating ablation models. For this purpose, we use the model of Reeh (1991) on a grid with 20 km spacing. This grid spacing is chosen because a version of an energy-balance model (Wal and Oerlemans, 1994) used almost the same grid. In this way, two models with the same resolution in space can be compared.

The energy-balance model has a time step of only 40 min in order to calculate complete daily cycles. The degree-day model uses monthly mean values as input. Because no climatological ablation profiles in the course of the ablation season are available, only annual ablation will be compared between the two models. If the mass balance is presented in this paper, then the accumulation distribution presented by Ohmura and Reeh (1991) has been added to the calculated ablation. The equations and constants of the energy-balance model as used in this study are identical to those in the reference experiment described by Wal and Oerlemans (1994). This model is an extension of the energy-balance model presented by Oerlemans (1991). The main differences are the more detailed description of the albedo and a higher resolution in time and space. In the energy-balance model, the albedo parameterization is formulated as a function of snow depth, snow age and water content of the surface. The time-scale for run-off of meltwater is taken to be constant.

Input for both models is elevation, latitude and accumulation on a regular grid with a 20 km spacing (Huybrechts and others, 1991; Letréguilly and others, 1991). Altogether, this gives 4177 grid points with ice cover, representing $1.67 \times 10^6\,\mathrm{km}^2$. An impression of the distribution of the grid points is given in Figure 2 as a function of the elevation and latitude. It can be observed that the majority of the grid points are located at a higher elevation, which is a direct consequence of the geometry of the ice sheet. The righthand side of the figure shows a north–south cross-section over the ice divide, indicating the two-dome (63° N and 72° N) structure.

It should first be noted that the temperature parameterizations in the degree-day model and the energy-balance model are not identical. The energy-balance model follows the formulation for temperature presented by Huybrechts and others (1991), whereas the degree-day model follows the formulation by Reeh (1991). As can be seen in the Appendix for the two degree-day models this might lead to rather different results.

The Greenland ice sheet can be characterized by four climatological latitudinal zones as shown in Table 1. The southernmost area can be regarded as the warm wet sector, the zone from 65° to 70° N as warm and dry, and the two northern zones as cold and dry. Although we realize that this latitudinal separation is arbitrary and a simplification of the various climate zones, the separation turns out to be useful for understanding the observed differences in the calculations.

A first bulk comparison between the degree-day and energy-balance models is the size of the ablation area. If we consider the reference cases for both models, we observe that in the degree-day model 10.5% of the modelled ice sheet is ablation area, whereas the energy-balance model predicts 12.7%. More important is that we observed that both areas overlap. Of the 532 grid points which belong to the ablation area in the energy-balance model, 417 points (i.e. 80%) also belong to the ablation

Table 1. Climatological characterization of the ablation zone of the Greenland ice sheet. To compose the table, the grid points used are those where there is ablation in one of the two models. Note that this selection is not identical to the ablation zone of one of the models

Zones °N	*Number of points*	*Mean elevation* m a.s.l.	*Mean annual temperature* °C	*Mean July temperature* °C	*Mean accumulation* m w.e.	*Classification*
60–65	215	1492	–10.6	2.2	0.92	Warm and wet
65–70	306	1328	–12.7	1.2	0.42	Warm and dry
70–75	167	1262	–16.0	–0.6	0.26	Cold and dry
> 75	338	879	–17.5	–0.6	0.22	Cold and dry

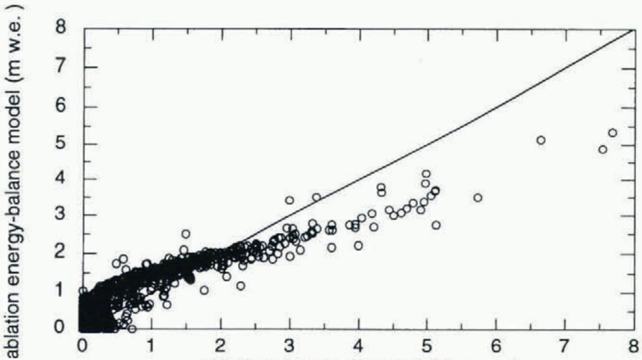

Fig. 3. The ablation of the energy-balance model (EBM) vs the ablation of the degree-day model (PDD) for all ice-sheet points (n = 4177).

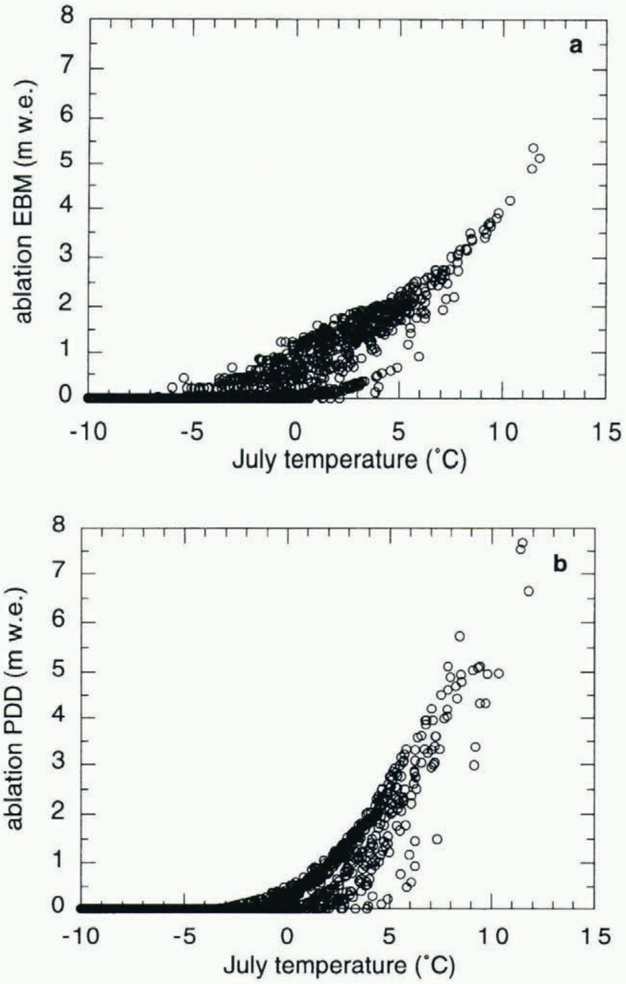

Fig. 4. The ablation as a function of the mean July temperature. (a) EBM; (b) PDD.

area in the degree-day model. The discrepancy in the size is probably due to a higher mean ablation for the energy-balance model, which produces more points in the ablation area higher up on the ice sheet. This result should, however, be considered with some scepticism because the accumulation distribution is identical for both models, which means that small differences in ablation are overruled by the accumulation. A more straightforward comparison is given in Figure 3. In this figure, the ablation of the energy-balance model is plotted as a function of the ablation of the degree-day model for all points. The figure also shows that there is a tendency towards high ablation values for the energy-balance model if the ablation is small, and towards higher ablation values for the degree-day model if the ablation is large. Summing all points of both models gives a 14% higher ablation for the energy-balance model than for the degree-day model, It is interesting to see whether the differences between both models are restricted to specific areas of the ice sheet. In Table 2 results for both models are given for different latitudinal zones. It can be seen that the energy-balance model produces a higher ablation in the northern areas. This seems to be in agreement with Figure 3, because these areas are characterized by relatively low values for the ablation (at least compared to the warm low-lying points in south Greenland). It can also be observed in Table 2 that, although the mean ablation is larger in the southern zones, a significant absolute contribution originates from the northern zones.

Figure 4 shows the ablation in both models as a function of the mean July temperature. The degree-day model shows some lines due to formulation of the latitudinal variation of the temperature-elevation gradient. This figure shows a larger scatter for the energy-

Table 2. Zonal distribution of the ablation of the Greenland ice sheet for a degree-day model (PDD) version (Reeh, 1991) and an energy-balance model (EBM) (Wal and Oerlemans, 1994). To compose the table, the grid points used are those where there is ablation in one of the two models. V is the volume of the ablation and M the mean ablation

Zones	*Number of points*	*PDD model*		*EBM model*		*EBM–PDD/PDD*
		V	*M*	*V*	*M*	*V*
°N		10^{11} m^3 w.e.	m w.e.	10^{11} m^3 w.e.	m w.e.	
60–65	215	0.68	0.79	0.71	0.83	+4%
65–70	306	1.15	0.94	1.10	0.90	–14%
70–75	167	0.31	0.46	0.42	0.63	+38%
>75	338	0.64	0.47	0.93	0.69	+46%
Total	1026	2.78		3.16		+14%

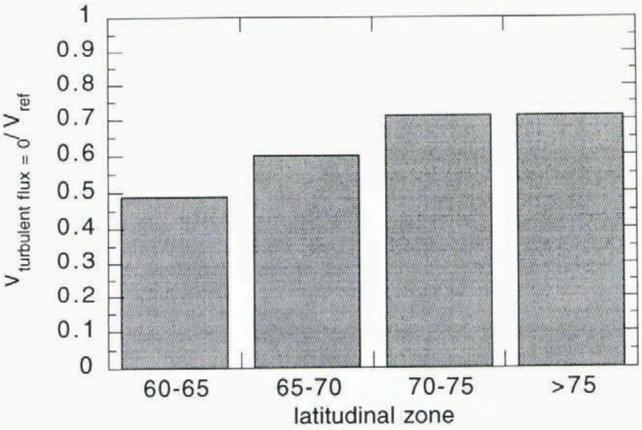

Fig. 5. The ablation per latitudinal zone scaled by the ablation in the reference experiment. The figure shows a decreasing contribution of the turbulent flux towards the north.

balance model, especially if the ablation is low. The ablation in the energy-balance model is due partly to a direct temperature effect via the turbulent heat flux but also to the net radiation balance. This means that even if the July temperature is below zero, ablation might occur, depending on the net radiation. A high July temperature, on the other hand, might result in very limited ablation because of a negative net radiation. The combination of these two effects explains the larger scatter in the energy-balance model for low ablation values. It helps us to explain the observed differences between the models.

The difference can be understood if we consider the contribution of the turbulent heat flux to the total ablation, the "direct temperature effect". Figure 5 shows the zonal distribution of the ablation for an experiment with no turbulent heat flux but keeping the albedo identical to the reference experiment. For the southern areas, where about 50% of the ablation is due to the turbulent heat flux, the two models yield comparable results. In the northern areas, where the positive net radiation balance is more important for the ablation (due to the low cloud amount), the energy-balance model predicts more ablation. Degree-day models can only predict significant ablation in the northern areas if very high values for the stochastic term are assumed, which would produce unrealistically high ablation values for the southern parts or a regional different degree-day factor should be prescribed.

To judge the performance of the two types of models, one needs to compare calculated mass-balance profiles with measured mass-balance profiles. This poses a problem. As demonstrated in the introduction, meteorological knowledge of the Greenland ice sheet is limited. The temperature parameterization is reduced to a standard period, namely 1951–60. This is, however, not the case with the accumulation distribution. To complicate the picture even more, no mass-balance measurements are available for this standard period. Mass-balance data which are useful for validating climatological models should cover several years of measurements. Only a few mass-balance records of more than 1 year are available and they are all from West Greenland. In this study, we use data from Nordbogletscher (61.5° N)

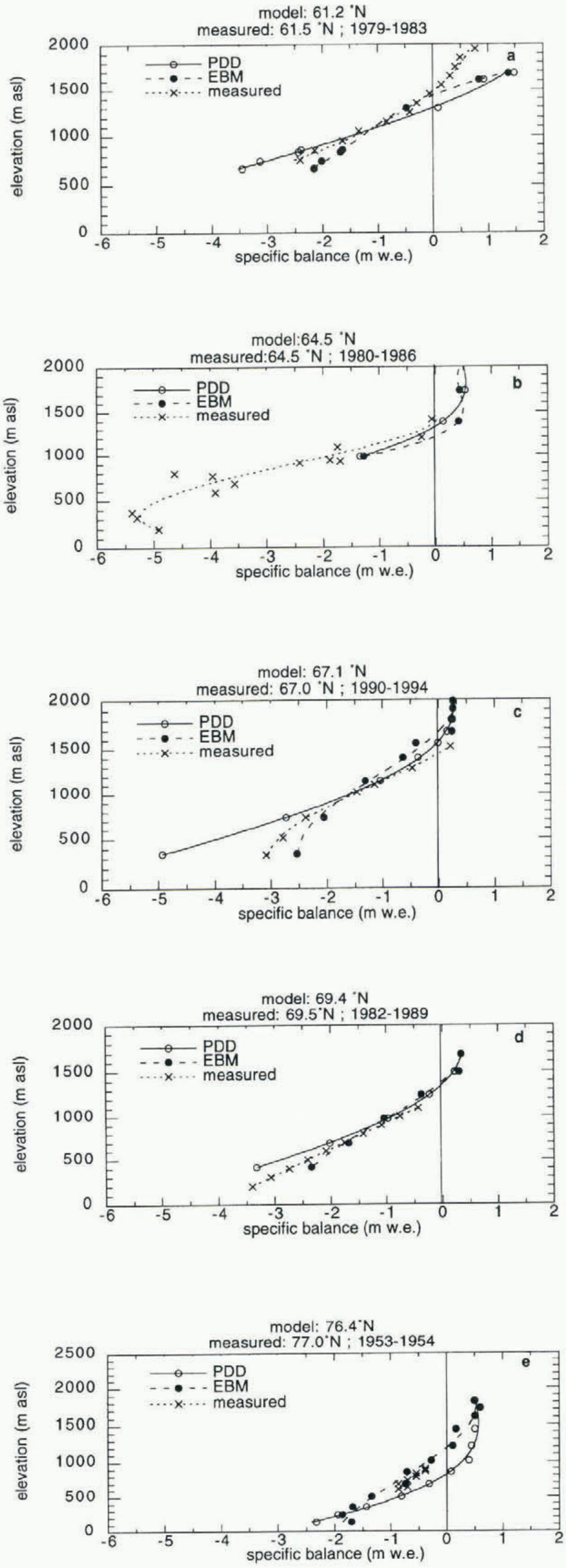

Fig. 6. Calculated and observed mass-balance elevation relationships at five locations in Greenland. PDD is the degree-day model presented by Reeh (1991). EBM is the energy-balance model. Points are observed or modelled specific balance. The lines are third-order polynomials. Data from 61.5° N (Clement, 1981, 1982, 1983, 1984), 64.5° N (Braithwaite and Olesen, 1989), 67° N (Wal and others, 1996), 69.5° N (personal communication from H. H. Thomsen), 76.7° N (Nobles, 1960).

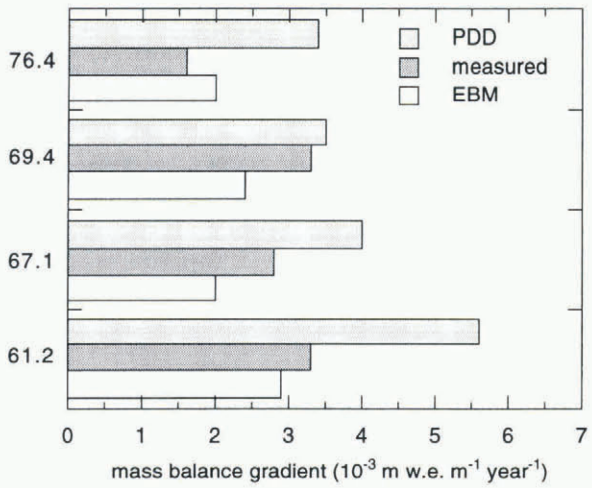

Fig. 7. Calculated and observed mass-balance gradients over the ablation zone. PDD is the degree-day model presented by Reeh (1991). EBM is the energy-balance model.

(Clement, 1981, 1982, 1983, 1984) covering the period 1979–83, from Qamanârssup sermia (64.5° N) (Braithwaite and Olesen, 1989) covering the period 1980–86, from Søndre Strømfjord (67° N) (Wal and others, in press) covering the period 1990–94 and from Påkitsoq (69.5° N) (Thomsen, 1985, 1987, 1988, personal communication; Thomsen and Reeh, 1986) covering the period 1982–89. To this data set from West Greenland, which covers at least 4 years of measurements, we add a 1 year record from north Greenland, Nunatarssuaq ramp 77° N (Nobles, 1960).

A problem with the available mass-balance records is that they are short and not synchronized with the meteorological input data; in addition, there is a scale problem. Measurements are only representative for a specific site or transect. The models used to calculate the ablation over the whole of Greenland have a grid size of 20 km, which means for instance that some areas with mass-balance measurements are very poorly represented in the models. For this reason, we selected grid points that are as close as possible to the measured sites in terms of latitude. Although calculations and measurements are obviously not at the same location and elevation, general characteristics can be derived.

In spite of these major drawbacks, the available specific-balance measurements are compared with the modelled ablation for five transects in different climate regimes. The results are shown in Figure 6. We can observe that the energy-balance model tends to underestimate the ablation (61.2° N, 67.1° N, 69.4° N) at lower elevation but the degree-day model tends to overestimate the ablation even more (61.2° N, 67.1° N, 69.4° N) at lower elevation. For 76.4° N no measurements are available at low elevation and for 64.5° N no representative grid points are available. Higher up in the ablation area, a more complicated picture arises. The energy-balance model produces good results at 61.2° N, 69.4° N and 76.4° N but tends to show too high ablation near 76.1° N. The degree-day model yields good results in this area, as well as near 69.4° N but tends to yield too low ablation at 61.2° N and 76.4° N for the upper ablation area. Altogether, a complicated picture arises. The mass-balance elevation profiles for the ablation area are characterized in Figure 7. This figure shows the mass-balance gradient for the two models as well as for the measurements. It can be observed that on average the energy-balance model yields mass-balance gradients which are closer to the measurements. The degree-day model performs reasonably well in central Greenland but overestimates the mass-balance gradient in south and north Greenland.

CLIMATE EXPERIMENTS

Although the insight of the simulated mass balance in the present-day climate is limited, ablation models are used to calculate the ablation of the Greenland ice sheet for various hypothetical climate scenarios. In this section, a few preliminary experiments are presented in order to provide some insight into the sensitivity of the different models. To begin with, we change the mean annual temperature by +1 K. A perturbation of this kind leads to an increase in the ablation in the two models. This extra ablation can be expressed in terms of global sea-level rise by dividing the ablation for the ice sheet by the surface area of the oceans ($3.62 \times 10^{14}\,m^2$). The results are shown in Figure 8. The uppermost bar shows the rise in sea level for a 1 K increase for the energy-balance model. An important detail is that the albedo is kept constant in time and space (compared to the reference experiment). This experiment shows the increase that results from increased turbulent heat flux and increased longwave radiation. Shortwave radiation is unchanged because albedo and cloudiness are fixed. This direct temperature effect is rather limited: a sea-level rise of only 0.14 mm $year^{-1}$. The albedo feed-back mechanism, due to the lower albedo of ice compared to snow, leads to a doubling of the increase in ablation as is represented by the second bar (counting from the top downwards). A comparable experiment can be performed with the degree-day models of Reeh (1991) and Huybrechts and others (1991). In these models accumulation is a non-linear function of temperature for the standard run. To

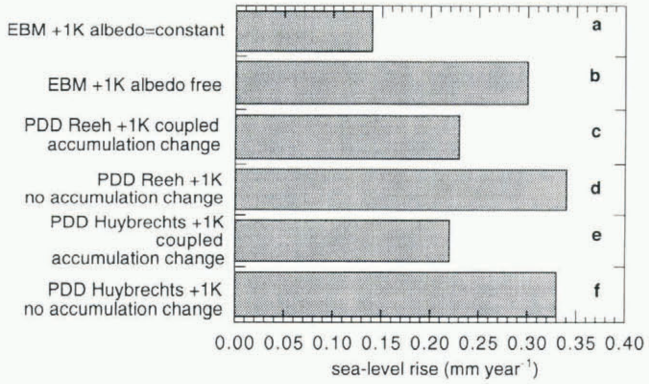

Fig. 8. Sea-level rise for a 1 K increase in the annual mean temperature for various models. EBM is the energy-balance model. Reeh is the degree-day model presented by Reeh (1991). Huybrechts is the degree-day model presented by Huybrechts and others (1991).

Table 3. The sensitivity of both models to a positive and a negative change in temperature. The table shows that both models are non-linear but the strength of the non-linearity is larger in the energy-balance model than in the degree-day model

	Energy-balance model Wal and Oerlemans (1994)	*Degree-day model Reeh (1991)*
	mm sea-level change year^{-1}	mm sea-level change year^{-1}
+1 K	+0.31	+0.34
–1 K	–0.18	–0.26
Sum	+0.13	+0.08

enable a comparison with the energy-balance model, in which accumulation is independent of temperature, this coupling is neglected. The calculated sea-level rise for the degree-day models is 10% higher (bars 4 and 6) than for the energy-balance model. Application of the coupling between temperature and accumulation reduces the increase in sea level from 0.33 to 0.22 mm year^{-1} (bars 3 and 5). This is an interesting phenomenon because the direct increase in accumulation for a 1 K increase is only 5% or 0.08 mm sea-level lowering per year. The reason for this discrepancy is the use of different degree-day factors for snow and ice. The increase in sea-level rise is therefore partly set off by a 0.11 mm sea-level drop as a result of the temperature–accumulation coupling. If we assume that the differences in the degree-day factor reflect differences in the albedo of snow and ice, something which is questionable, one can say that the degree-day model has an implicit albedo feed-back mechanism, like the energy-balance model, although the strength is less. Note that the differences for a 1 K perturbation in the two degree-day models are coincidentally comparable, in spite of the differences (see Appendix).

An important aspect of a model is whether its sensitivity to an external parameter is linear or not. This kind of experiment yields some insight into the sensitivity of the ablation to natural variability of a climate parameter. Here, we consider for both models the change in mass balance for a variability of 1 K in the temperature. The response of the models to a positive change in temperature has already been considered in the previous paragraph. To calculate the sensitivity to a decrease in temperature, we start with the present-day equilibrium state of the energy-balance model. Accumulation is kept constant so that both models can be compared. The results are given in Table 3.

This table shows that both models are non-linear. The change in mass balance for a positive change in temperature is larger than for a negative change. The strength of the non-linearity is, however, much stronger in the energy-balance model than in the degree-day model. This means that the natural variability is more important for the energy-balance model than for the degree-day model. In fact, one could argue that the sensitivity to natural variability should be taken into account for calculation of the sensitivity of a specific climate parameter to obtain an insight into what really changes as a result of climate change. The discrepancy in the response to natural sensitivity would increase the difference in the sensitivity of the two types of model even more.

One can argue that a comparison of the sensitivity is only useful when the reference cases are identical. This is not the case in the previous experiments, because we opted for identical input and no changes in the models compared to the publications of Reeh (1991) and Wal and Oerlemans (1994). A simple way of obtaining the same amount of ablation over the entire ice sheet is to tune the degree-day model to the reference case of the energy-balance model by adjusting the value of the statistical term, σ, to 5.0 (instead of 4.5 as Reeh (1991) used). Starting from this new reference state yields a sea-level change of 0.37 mm year^{-1} (instead of 0.34 mm year^{-1}) in the degree-day model for a 1 K temperature perturbation. This means that the change in sea level for a 1 K temperature rise is 20% higher for the degree-day model than for the energy-balance model, whereas 10% can be observed in Table 3.

A more rigorous comparison of the sensitivity to a temperature perturbation is shown in Figure 9. This figure shows that for small (positive) changes in temperature, the degree-day model and the energy-balance model yield fairly similar results but the results diverge for larger perturbations of the reference temperature. It can also be observed that the result does not seem to depend on the exact reference state, since the results of the degree-day (PDD) model for $\sigma = 4.5$ and $\sigma = 5.0$ are nearly identical. The divergence for larger perturbations implies that using both models in climate scenarios with a variable temperature forcing the result of the energy-balance and degree-day models might differ considerably even if the forcing is not latitude-dependent. If we express the sensitivity in mm sea-level rise per year per K, the sensitivity of the energy-balance model increases from

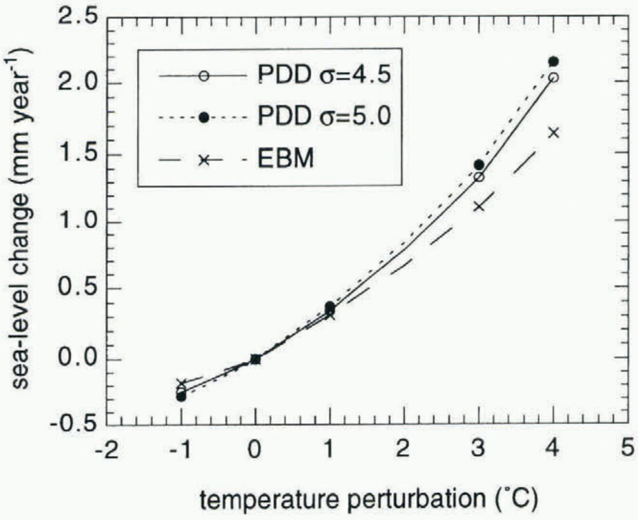

Fig. 9. Sea-level rise as a function of the temperature perturbation for the degree-day model presented by Reeh (1991) and the energy-balance model presented by Wal and Oerlemans (1994).

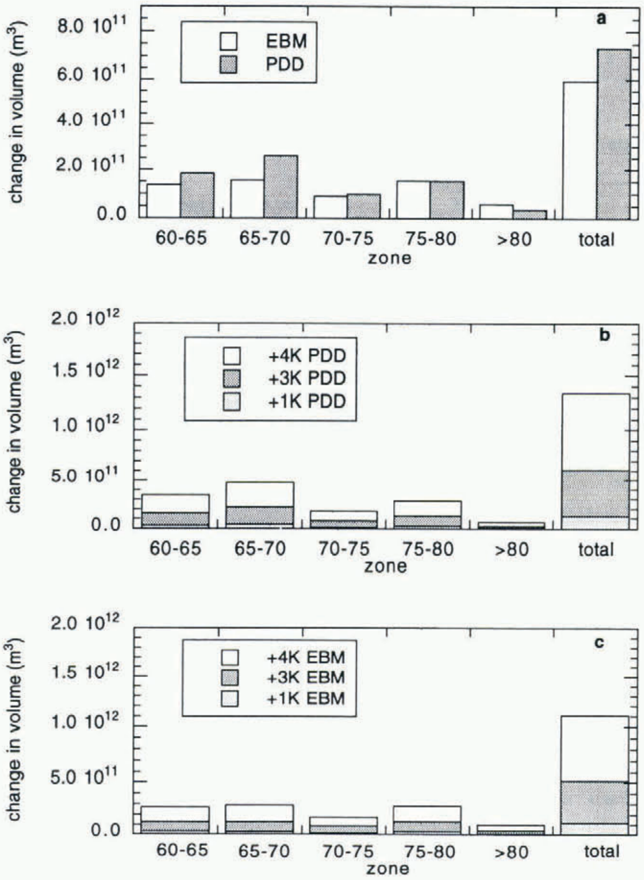

Fig. 10. The change in volume of ablation for different latitudinal zones, for a 4 K increase for both models (a), for +1, +3, +4 K for the degree-day model (b), and for +1, +3, +4 K for the energy-balance model (c).

0.31 mm year^{-1} K^{-1} for a 1 K perturbation to 0.58 mm year^{-1} K^{-1} for a 4 K perturbation.

So far, the perturbations considered are those which are uniform in space or latitude-independent. In global climate models, changes are expected to be higher closer to the Pole. For this reason, a simple sensitivity analysis is composed which gives insight into the latitude-sensitivity of both models. Figure 10a shows the change in volume in response to a 4 K temperature increase for both models for varying latitudinal zones as well as the change in volume for the whole ice sheet. This figure shows that the difference between both models is entirely due to the sensitivity of the two southern zones. Figure 10b and c shows that this feature can also be observed for a 3 K temperature perturbation. For a 1 K perturbation, differences are small which is in agreement with the overall results shown in Figure 9. The larger sensitivity of the energy-balance model in the most northern zone is not important for the overall increase in ablation. So, in spite of the large differences in the reference case for the northern zone, as given in Table 2, only minor differences occur in the sensitivity. This means that the results of applying a forcing function with a larger perturbation in northern areas are not different from the results of an experiment in which a uniform temperature perturbation is applied over the entire ice sheet. With this in mind, we apply the Bellagio scenario, a 0.3° C increase per decade, for both models. The results are shown in Figure 11. The degree-day model predicts a 32% higher sea-level rise than the energy-balance model over a period of 100 years.

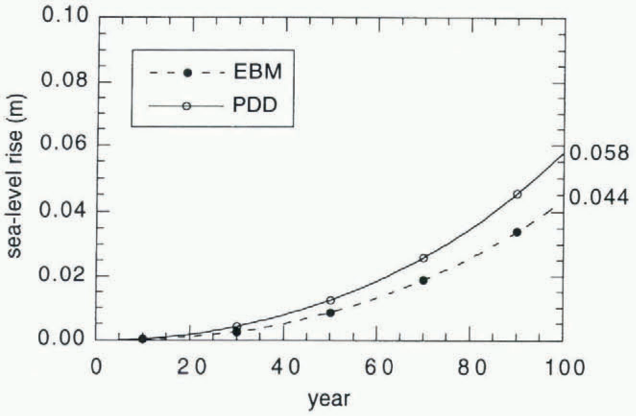

Fig. 11. The predicted sea-level rise for the Bellagio scenario for both models.

CONCLUSIONS

In spite of the limited mass-balance data available and the problems involved in comparing ablation models and mass-balance measurement, we conclude that the energy-balance model produces better results than the degree-day model (Fig. 7). The differences between the two models for the present state are largest in the northern areas (Table 2) where data are scarce.

The sensitivity of the degree-day model is 20% larger than in the energy-balance model, for perturbations of 1 K, if the two models are tuned to the same reference ablation. The difference in sensitivity is concentrated in the southern part of Greenland (Fig. 10a).

For larger perturbations, the sensitivity of the two types of model diverges (Fig. 9). This results in a 32% higher sea-level rise over a period of 100 years (Fig. 11), if the temperature increases 0.3°C per decade and the natural variability is neglected. Including the natural variability would increase the difference between the two models even more. Although the two types of model diverge, one should realize that the models both show that the sensitivity increases for larger temperature perturbations. This means that predictions for future sea-level rise cannot be based on a sensitivity parameter which is independent of the temperature perturbation itself.

We therefore conclude that the sensitivity used to calculate sea-level rise as presented by Warrick and Oerlemans (1990), indicating a similar and constant sensitivity for degree-day models and energy-balance models, needs to be reconsidered.

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APPENDIX

Here are a few notes on the formulations of the degree-day models presented by Reeh (1991) and Huybrechts and others (1991). Chronologically, the first universal degree-day model was the one presented by Reeh (1991). This model has been applied for four mass-balance–elevation profiles. Citing Reeh (1991): "Using the present surface elevation of the ice sheet as a boundary condition, the total amount of melt from the ice sheet, as determined from the melt-rate model, amounts to 281 km^3 ice year^{-1} (Huybrechts et al. 1991)". On the other hand, Huybrechts and others (1991) referred for further details (a comparison of calculated and measured values) to Reeh (1991). But both models used different parameter settings, so a close-up seems justified.

Three differences are recognized between the two degree-day model formulations:

The temperature parameterization.
The degree-day factors.
The value for the stochastic term (σ).

We compare the results of the two models here in terms of calculated ablation for the whole Greenland ice sheet, without presenting the details of the differences. Input for both models is elevation, latitude and accumulation on a regular grid with 20 km spacing (Huybrechts and others, 1991; Letréguilly and others, 1991) as used in the comparison between the degree-day model of Reeh (1991) and the energy-balance model (Wal and Oerlemans, 1994). Figure 12 shows the ablation for various parameter settings scaled by the calculated ablation of the experiment presented by Huybrechts and others (1991), which amounts to 281 km^3 ice year^{-1}. The second bar in the figure shows that, if the July temperature parameter-

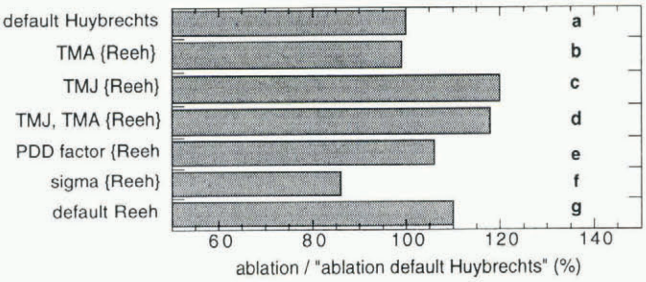

Fig. 12. The ablation for the degree-day model of Reeh (1991) for various settings scaled by the degree-day model of Huybrechts and others (1991). TMA is the annual mean temperature, TMJ is the July temperature, PDD factor are the degree-day factors for snow and ice and sigma is the stochastic term.

ization as presented by Reeh (1991) is used and all other variables are as in the reference experiment of Huybrechts and others (1991), a 20% higher ablation is calculated. From the abovementioned discrepancies, two yield a higher ablation, the temperature parameterization +18%, the degree-day factors +6% and one yields a lower ablation, the stochastic term −14%. Applying all three differences at once, as shown by the lower bar in Figure 12, which is equal to the reference experiment of Reeh (1991), yields a 10% increase in the ablation.

These considerable differences do not justify the interpretation by Reeh (1991) of his model version in terms of ablation for the whole ice sheet, based on Huybrechts and others (1991), nor does it justify the implicit validation of the version used by Huybrechts and others (1991) by referring for details to the Reeh version.