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COASTAL AND POLAR ATMOSPHERIC REGIONAL MODELING

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HOW GOOD ARE OUR MODELS?

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1. INTRODUCTION

Regional modeling is a powerful tool for applications ranging from local high-resolution short-term weather forecasting to regional climate modeling. It makes it possible to represent regional physiography with a higher degree of detail and still retain numerical efficiency. However, as global weather-forecast models approaches higher and higher resolution, two of the remaining most important uses for regional modeling will be regional climate modeling or the use of models as research tools for the development of parametrizations for use in global models. Global models will remain difficult to use directly for model development because of two reasons. First, the non-linearity of the atmosphere makes it very difficult to isolate individual causes-and-effects in the error cascade – changing one property in the model makes everything else, including the synoptic-scale motions, change and it becomes very difficult to interpret the reasons for a particular result. In a regional model, on the other hand, results from a global data assimilation cycle can be prescribed at the lateral boundaries. Using a limited-size regional domain implies a strong control over the regional or synoptic scale atmospheric flow. It also facilitates a direct comparison between model results and real observations. Second, global climate models will remain limited in spatial resolution, but we can today afford to run regional models for extended integrations at resolutions likely to be typical in the next generation global climate models. Many errors in model physics are in shorter weather forecasts efficiently hidden by advances in data assimilation. Remaining systematic errors may be small for weather forecasting, where the data assimilation cycle continuously corrects them, but can be devastating in climate modeling.

Coastal conditions are is among the most difficult to model. The step-change in surface properties along coastlines represents a special challenge for models. In particular, the model's boundary-layer description needs to cope with very rapid transitions, often from unstable to stable conditions or vice versa. Low-level wind-speed jets are frequent along many coastlines. Low-level wind maximums are also common in katabatic flows, often found over melting glaciers for example in the continental Arctic and in Antarctica, and low-level jets are often found also in the Arctic boundary layer. In polar regions, the ice edge is basically a coastline from a meteorological perspective. Additionally, in the Arctic boundary-layer processes are critical since they determine ice drift and melt.

Common to all these examples are complex wind-speed profiles, surface heterogeneity and stably stratified boundary layers. Situations where we perhaps expect models to have problems. In this paper we intend to review our capability to model complex and stable boundary layers in coastal and arctic environments. Results from models and field experiment from the US west coast, from Island and from the central arctic will be used to illustrate the state-of-the-art models capability to correctly describe the atmospheric boundary layer during such complex conditions.

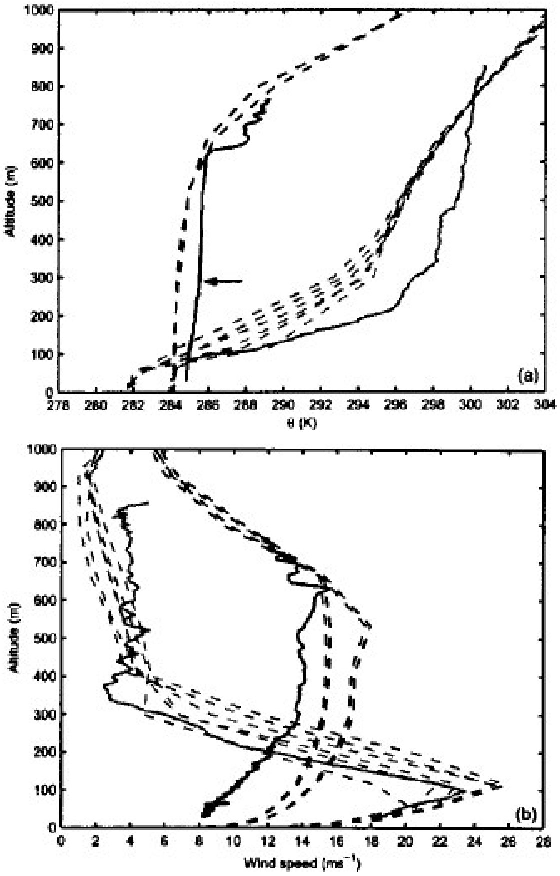

Figure 1. Example of (a) potential temperature and (b) wind speed profiles in a US West Coast flow before and after passing Cape Mendocino in northern California.

2 MODELS AND OBSERVATIONS

There are several ways to test model behavior against data. In the examples below, we will use case studies, where a particular event is studied and model results are compared to data, controlled hypothetical experiments where a model is set up in a controlled

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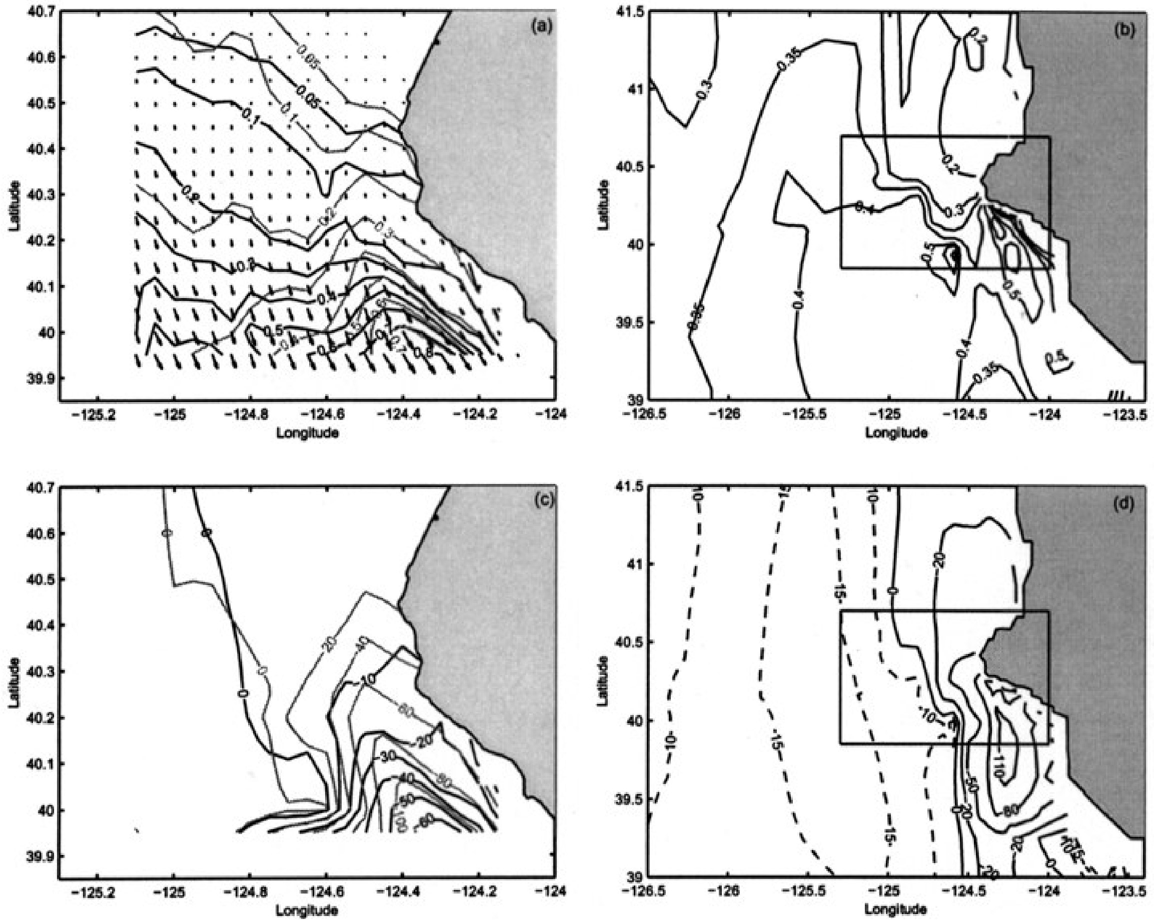

Figure 2. Horizontal plots of (a, b) surface stress and (c, d) buoyancy flux from (a, c) observations and (b, d) model. Note that the observations include both (black) direct eddy correlation and (gray) bulk-flux estimate.

fashion and many models are compared, and long integration with regional models where systematic errors are allowed to grow.

2.1 EXAMPLE 1: COASTAL JETS AND INTERNAL BOUNDARY LAYERS

Coastal flows often exhibit jet-like structures that are enhanced as the flow passes capes and points. During certain conditions, enhanced upwelling causes a significant lowering of the sea surface temperature and thus a stably stratified internal boundary layer. Figure 1 shows one such case, from the *Coastal Waves 1996* project (Rogers et al. 1998) where a well-mixed boundary layer with a broad coastal jet collapses to a stable boundary layer and a strong and sharp jet as the flow passes Cape Mendocino in northern California. This happens due to the formation of a hydraulic phenomenon called an "expansion fan" (Brooks et al. 2003).

Figure 2 shows the observed (left panels) and modeled (right panels) surface stress and buoyancy flux. The patterns are quite similar, but the magnitudes differ by a roughly a factor of two. The left two panels shows two values from the measurements; direct eddy-correlation results and the more indirect so called bulk flux results. It is interesting to note that the model values compare better with the latter, than with the direct measurements. This points to a special problem in this model which it shares with most models with a with higher order turbulence closure. While the model closure itself can respond to horizontal heterogeneity and the local balance between source and sink terms, the prognostic higher order moment equations, such as that for the turbulent kinetic energy, needs a lower boundary conditions. This is most often derived from standard surface layer similarity relations, requiring stationarity and horizontal homogeneity – precisely the restrictions that higher-order closure should be free of. Still,

Figure 3 shows two examples of a scaled or statistical representation of the momentum flux. First, the momentum flux profiles are scaled by the value of the surface flux while the height is scaled by the boundary-layer depth, and in the second example, so called local scaling is used. In both cases, the markers are from the model while the lines are from the corresponding measurements. Thus, even though the modeled surface fluxes are off by a factor of two, the scaled turbulence shows the expected functional behavior.

2.2 EXAMPLE 2: KATABATIC JETS

Another example of a persistent jet-like vertical wind speed profile in combination with a stably stratified boundary layer is found for katabatic flows. These occur

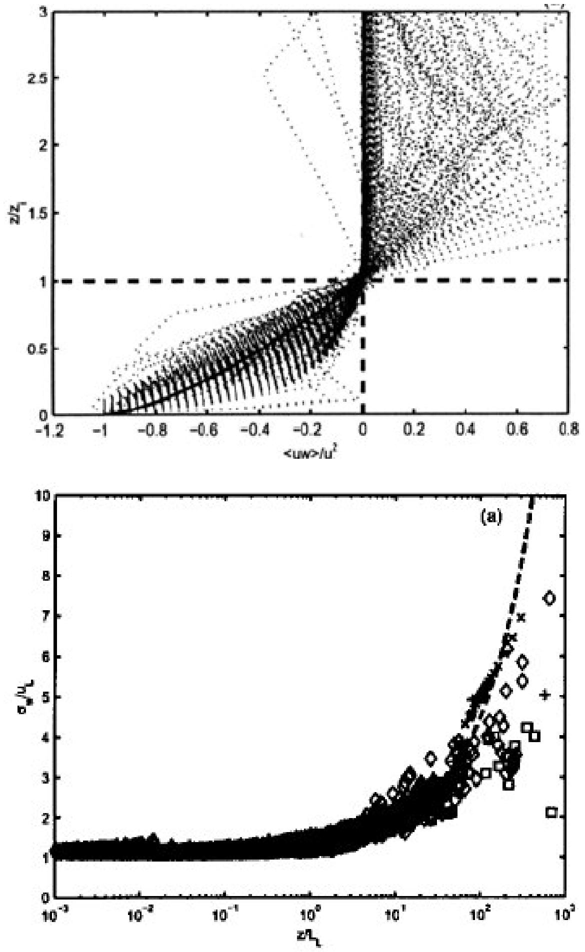

Figure 3. Scaled modelled turbulent momentum flux from the case in Figure 1 – 2, using traditional scaling (top) and local scaling (bottom).

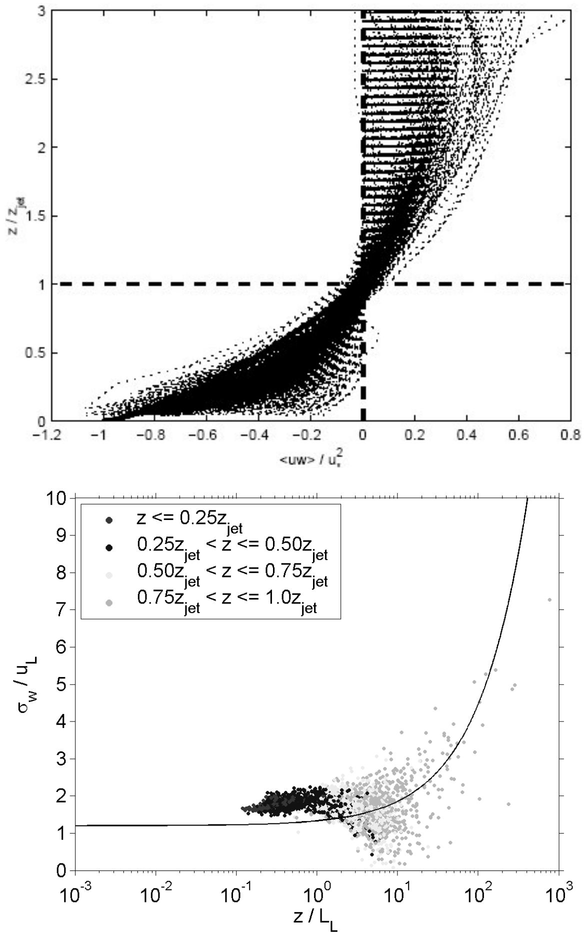

Figure 4. Same as Figure 3, but for a katabatic jet using a different model.

frequently over major glaciers, such as on Greenland and Antarctica. The example here is from Vattnajökull on Island, where katabatic flows are very predominant over the summertime melting glacier (Söderberg and Parmhed, 2004). In this case two mechanisms contribute to making this flow persistent. First, the melting keeps the surface temperature near zero while the katabatic flow itself causes an adiabatic heating of the air. Second, the jet-like wind speed profile itself generates a vertical structure that isolates the near-surface flow from propagating waves; this also happens also for the coastal jet.

Figure 4 shows modeled turbulence statistics for the katabatic jet, similar to that for the coastal jet. The results are very similar in spite of the fact that there are orders of magnitude differences in the geometry for these two cases.

2.3 HOMOGENEOUS STABLE BOUNDARY LAYER

In the GEWEX Boundary-Layer Study (GABLS, Cuxart et al., 2004), the first experiment is an idealized hypothetical case, based on LES results, where a case with relatively strong wind is exposed to a moderately fast constant surface cooling. Figure 5 shows some results from this experiment, using the output from 19 different single column models, and reveals a very interesting result. This figure shows profiles of the turbulent momentum flux from eight operational weather-forecast models to the left and from eleven research-type models to the right; the shaded region shows the spread of the eight participating LES. There is a substantial scatter between the different 1-D models, much larger than the scatter between the LES shown by the gray shading.

The most important feature in these results is, however, that the operational models all systematically overestimate the momentum flux compared to the ensemble of 1-D research models. This is true also for the sensible heat flux (not shown). However, scaling the individual profiles with their corresponding surface values and the height axis by the individual models boundary-layer depth makes all the curves collapse roughly on one line (Figure 6). Thus is appears a general feature that models produce reasonable scaled turbulence statistics, but that the actual turbulent fluxes vary widely between different models even under these highly idealized conditions applied exactly the same to all the models.

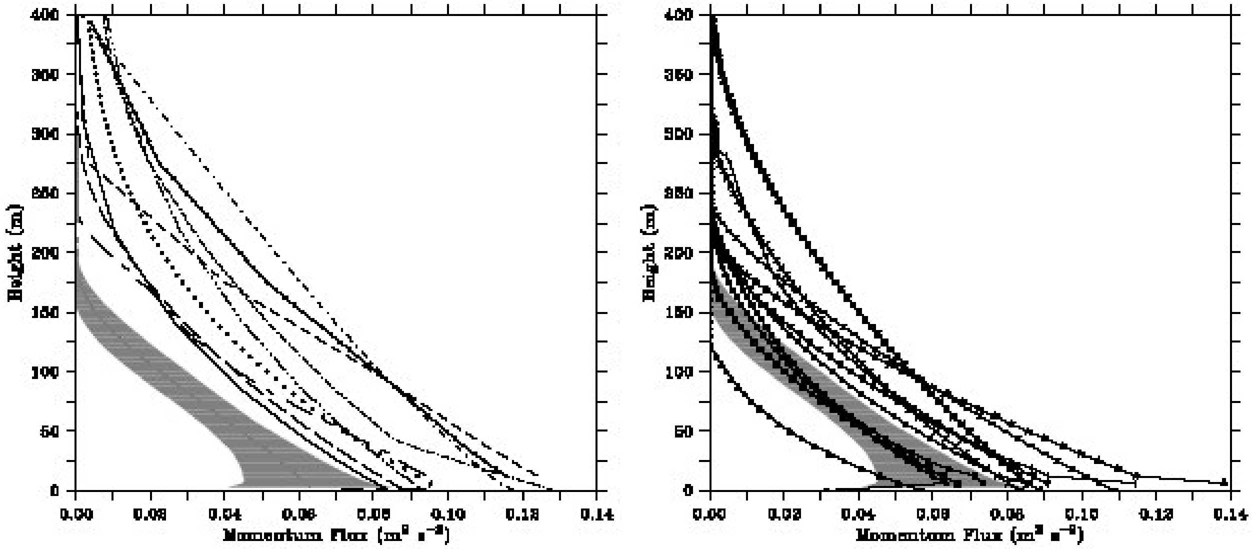

Figure 5. Profiles of turbulent momentum flux in (left) eight operational models and (right) eleven research models, all run in single-column configuration for exactly the same boundary conditions (from GABLS experiment #1).

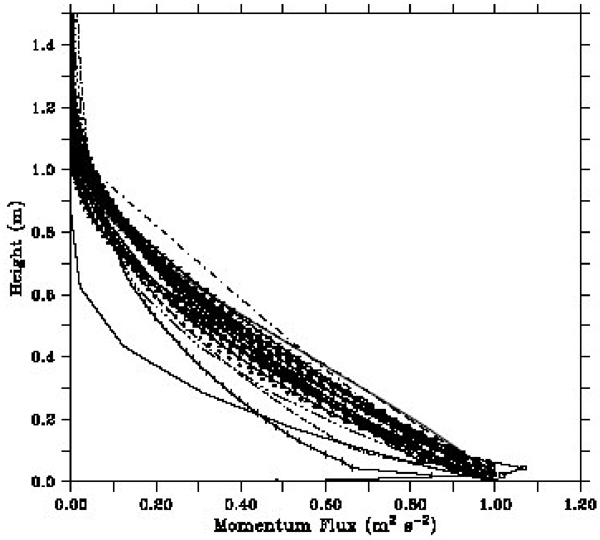

Figure 6. Same as Figure 5 bu the scaled profiles fo all 19 models (from GABLS experiment #1).

The fact that operational models systematically have larger turbulent fluxes is possibly related to the effect of the surface friction – and the corresponding cross-isobaric mass flux – on the evolution of synoptic scale pressure systems. To little frictional turning of the surface wind, causes a to small cross-isobaric mass flux, which translates into a slower spin-down of cyclones (Svensson and Holstslag, 2004). For some reason it seems, that this mass flux is to small in almost all operational models for a given surface condition. This also means that the relationship between the actual surface cooling, the turbulent surface fluxes and the wind speed must be different in operational models compared to LES.

Believing that LES somehow gives an accurate, or at least an internally consistent, description of boundary-layer turbulence, means that the surface turbulent fluxes in operational models – and presumably also global climate models – must be less than realistic. Basically, it must therefore be impossible in such models to correctly model both the surface temperature and the turbulent surface heat flux at the same time, unless some other compensating error is introduced. The actual cause of this dilemma is still quite not understood.

2.4 ARCTIC CLIMATE REGIONAL SIMULATIONS

In the light of the previous example, it is interesting to attempt a long integration with regional models in an area where the surface heat fluxes are critical to the regional climate – the Arctic.

The ARCMIP program (Curry and Lynch, 2002) is designed to attempt exactly that. Using the same model domain, the same surface forcing including specified sea- and ice-surface temperature and the same analyzed lateral boundary conditions, six models attempt to simulate the SHEBA-year (Uttal et al., 2002). The observed surface fluxes, near surface measurements and soundings serve as a test-bed for all models that are also compared to each other.

Figure 7 shows the 2-meter temperature for two three-month periods for six participating regional models. The models mostly follow the observed temperatures, as expected since the surface temperature was prescribed the same in all models. However, there are quite substantial differences between the models and many models sometimes show rather large errors, especially in winter when stable conditions with strong surface inversions are common. Figure 8 shows scatter-plots of friction velocity for all models. Some models deviate substantially, but mostly the friction velocity is surprisingly accurate. In fact, this result is better than that shown for the more idealized example in the previous example. However, this is not too surprising since these models must have a reasonable surface friction *on average* to

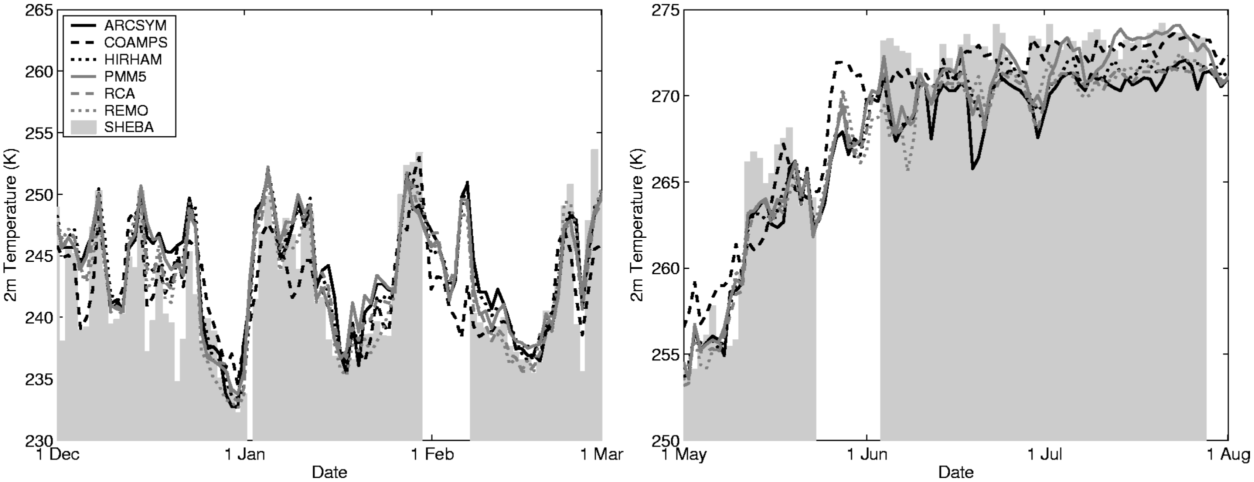

Figure 7. Simulated, with six regional models, and observed 2-meter temperature for the SHEBA year, for three (left) winter and (right) summer months.

be at all useful as forecast models – to have the correct synoptic scale flow – while the scatter is very large reflecting the varying conditions over a full year. Some models have a systematically high friction velocity, which sometimes is consistent with a low-level wind bias. The surface pressure (not shown) is, however, described very accurately by all models.

The real problems become apparent when the surface heat fluxes are investigated – Figure 9. None of the models show any skill in describing these heat fluxes. None of the models are similar to any of the other models and the correlation coefficients between the model results for either sensible or latent heat flux is typically below 0.3. Worse, the accumulated error (not shown) in both heat fluxes is easily an order of magnitude larger than the observed accumulated flux. In the light of the GABLS results, this is not surprising. Accumulated over a full year, these errors are to a degree somewhat compensating so that the error in the total energy flux is no so large, however, for the wrong reason.

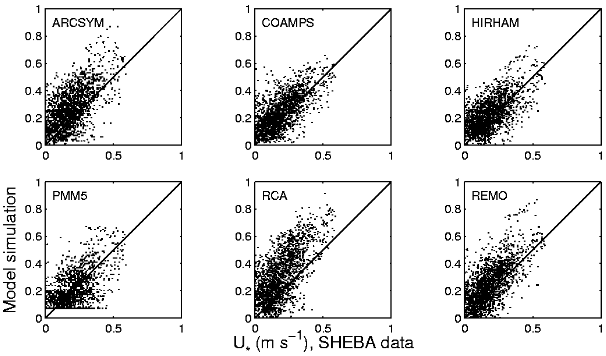

Figure 8. Scatter-plots of friction velocity for the one-year SHEBA ARCMIP-simulation.

Interestingly, if these fluxes are plotted in a different way, investigating their functional behavior, the results are – again – much better. Figure 9 shows the fluxes scaled by the corresponding 10-meter scalar wind speed plotted against the low level (2 meter minus surface) difference. The quasi-linear behavior in the scaled heat flux as a function of the near-surface gradient corresponds to the value of a bulk-transfer coefficient. Thus, again the scaled fluxes behave reasonable while the actual fluxes show no or little realism when compared to the observations.

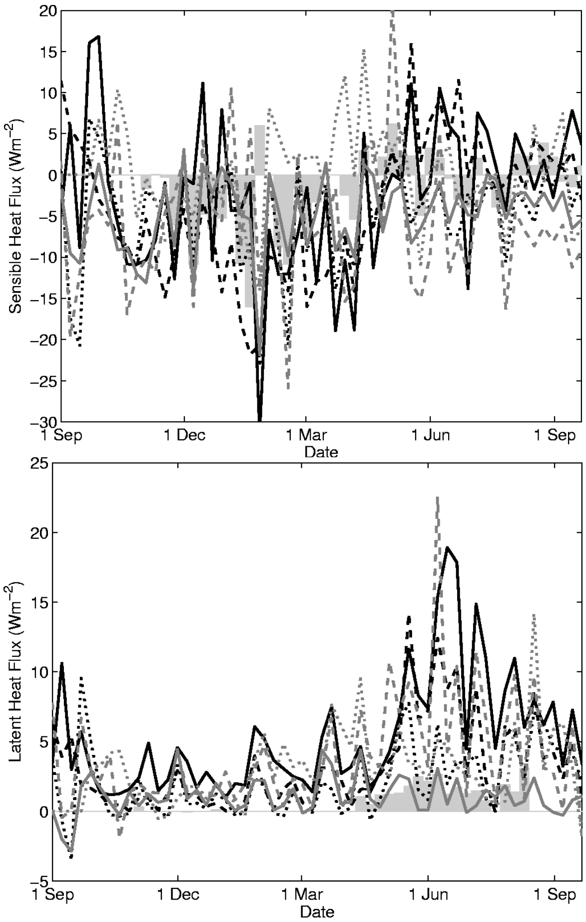

Figure 8. Modeled (top) sensible and (bottom) latent heat flux from the six ARCMIP-models for the SHEBA-simulation.

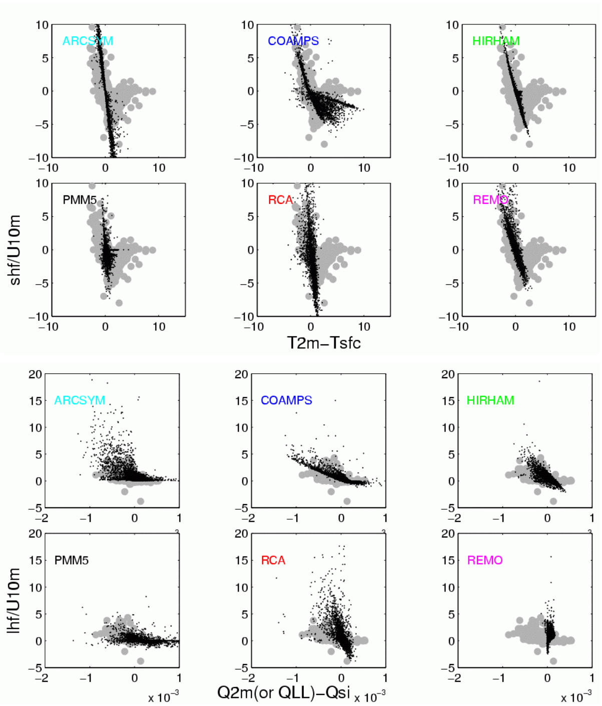

Figure 9. Modeled (top) sensible and (bottom) latent heat flux scaled by wind speed plotted against the low-level gradient, from the six ARCMIP-models in Figure 8.

3. DISCUSSION

The results shown in this paper have several common features. It seems that regional model is very powerful to simulate both high-resolution details of the flow in very complex situations and the synoptic scale variability in quite long controlled simulations, where analyzed “weather” is driving the models at the lateral boundaries. Also, as long as functional dependencies are considered, for example applying different scaling, the modeled turbulence is also following the observations quite well. This is not surprising, as these normalized behaviors of the turbulent properties forms the backbone of developing such parameterization schemes.

The actual fluxes, on the other hand, seldom follow the observed behavior and the errors in the fluxes are often very large. This seems to a particular problem for stable stratification. In the Arctic, for example, the result are large errors in the exchange between the atmosphere and the ocean. If for example the ARCMIP models where to be coupled to ocean models this would result in very different and probably erroneous development of the sea-ice.

We believe this is due to the way these models were developed. They were developed to conform to standard observations of standard variables such as 2-meter temperature, 10-meter winds and 500 hPa surface heights and not to any measured fluxes. Thus, scaled dependensies of turbulent parameters were applied and adjusted so that synoptic scale development was accurate. In the case when – for reasons still not understood – the cross-isobaric mass flux was insufficient to obtain the observed synoptic scale behavior of weather systems, the momentum flux was adjusted so that the net effect was optimal. The whole system then adjusted to a state with unrealistic turbulent fluxes at the surface. As long as the weather forecast capability is the only objective with these models, this objective was met. The real problem arise when the same type of models are applied to climate, and even worse climate change, studies. As the climate – and the climate change – is to a large extent driven at the surface by the surface fluxes, the reliability of these models come in question.

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