# Standalone ECBILT Experiments

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## 1 Introduction

The idea here is to do some experiments with a standalone version of the ECBILT 3-level atmosphere model to decide whether it's a suitable candidate for coupling into GENIE. The two main things to consider here are the speed of the ECBILT model and how good its climatology is. To investigate these things, I've done a quick first comparison with a HadAM3 simulation (BRIDGE simulation `tcszd`). I've also done some investigational work to help think about how hard it would be to couple ECBILT to GENIE, and to look at potential problems with the ECBILT model parameterisations for likely GENIE applications.

There are two versions of ECBILT that could be used for this comparison. The first is already coupled into the LOVECLIM EMIC, so would require some work to decouple it and set it up for standalone operation. The second is the original standalone ECBILT model[1], which is what I'm going to start with. It has a couple of deficiencies compared to the version included in LOVECLIM, but it's good enough for a quick first look. The main deficiency of the standalone ECBILT version is that it's not possible to change GHG forcings. This is because of the way the LW radiation scheme works: it's an empirical fit to LW radiation absorption from the GFDL GCM. I'm not yet sure what GHG conditions that fitting was done against, but I'm going to press on assuming that it was pre-industrial, as for the UM simulation. For applications in GENIE, we obviously need to be able to change the GHG concentrations so, if results from the first experiments with the standalone ECBILT are promising, I'll probably just transplant the newer LW radiation scheme from the LOVECLIM version of ECBILT (which treats GHGs explicitly) into the standalone ECBILT.

The approach I'm going to take to model validation here is just to convert boundary conditions from a suitable HadAM3 run to the form required to drive ECBILT, do the same sort of atmosphere-only simulation as done in the HadAM3 job and to compare the parts of the climatology most important for long-term GENIE simulations between the two models (also looking at model performance along the way).

As a first simple attempt, I'm going to leave all ECBILT input files unchanged from their defaults except for SST and sea-ice forcing, which are adapted from the HadAM3 simulation. This approach means that there's no need to convert land/sea masks, land cover types, the lake mask used by ECBILT, and so on. If we decide to go further, I'll do simulations using a land/sea mask and other boundary conditions based on the HadAM3 data (probably also updating the ECBILT LW radiation scheme as mentioned above).

## 2 Code and test platform setup

All the experiments reported here are performed on a machine running Arch Linux (rolling release as of 18 January 2015), with a 3 GHz Intel Core i5-3330 CPU and 16 Gb of main memory. All test runs were performed on a lightly loaded machine. Very few code changes were needed to get the standalone ECBILT code to build with the compiler used (GFortran 4.9.2).

[1] Downloaded from here `http://knmi.nl/~selten/pro_ecbilt.html`.

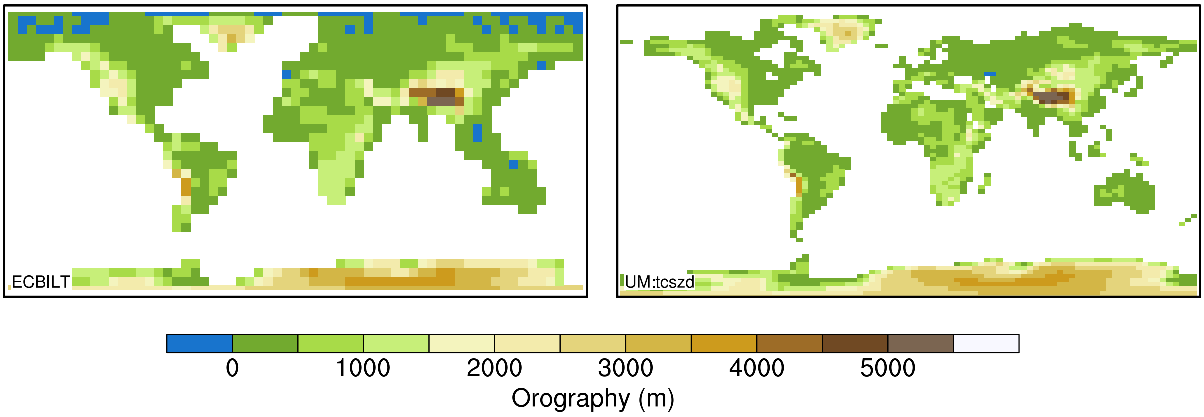


Figure 1: ECBILT and UM orography and land/sea masks used for comparison experiments.

# 3 Experiment #1

- Run name: `expt-1`.
- Original standalone ECBILT code, with only minimal changes for compilation.
- SST and sea-ice forcing converted from UM `tcszd` experiment.
- Simulation length: 100 years; spin-up: 70 years; analysis: 30 years.

## 3.1 Boundary conditions

Boundary conditions to run the standalone ECBILT model were derived from the BRIDGE `tcszd` HadAM3 simulation. This is a 100-year pre-industrial atmosphere-only simulation with prescribed climatological SSTs and sea ice.

In order to get an initial ECBILT simulation set up quickly, I decided to convert only the SST and sea ice forcing from the HadAM3 simulation, keeping the original ECBILT land/sea mask, orography, lake mask and land surface conditions (e.g. albedo), GHG concentrations and so on. Modifying these latter conditions to match HadAM3 will take more work than the relatively simple SST and sea ice regridding. I'll go ahead and do that if the results from the first simulation are encouraging enough.

Figure 1 shows the land/sea mask and orography for ECBILT and HadAM3 for comparison. One comment needs to be made about the ECBILT land/sea mask here: although some areas that should be ocean are treated as land in the land/sea mask, in particular the Mediterranean, the Great Lakes and the South China Sea, these grid cells *are* treated appropriately as water areas, via the use of a seperate lake mask identifying grid cells that have a significant water fraction.

### 3.1.1 SST and sea-ice

Conversion of SST and sea-ice from the HadAM3 boundary conditions to the form needed by ECBILT is pretty straightforward.

For the SST, the HadAM3 boundary conditions are given as a monthly climatology of SST. ECBILT requires daily SST on a different grid, so I take the HadAM3 monthly SST fields, Poisson fill to get rid of missing values, regrid to the ECBILT grid, mask with the ECBILT land/sea mask, then use independent periodic interpolation in time at each grid point to generate a daily SST climatology. This data is then converted to the binary format read by ECBILT.

For sea ice, again HadAM3 again uses a monthly climatology, but ECBILT uses a “birth/death” map showing, for each grid cell, the month of the year where sea ice first appears and the month when it disappears. To generate a sea ice driver file in this form, the HadAM3 monthly sea ice data is

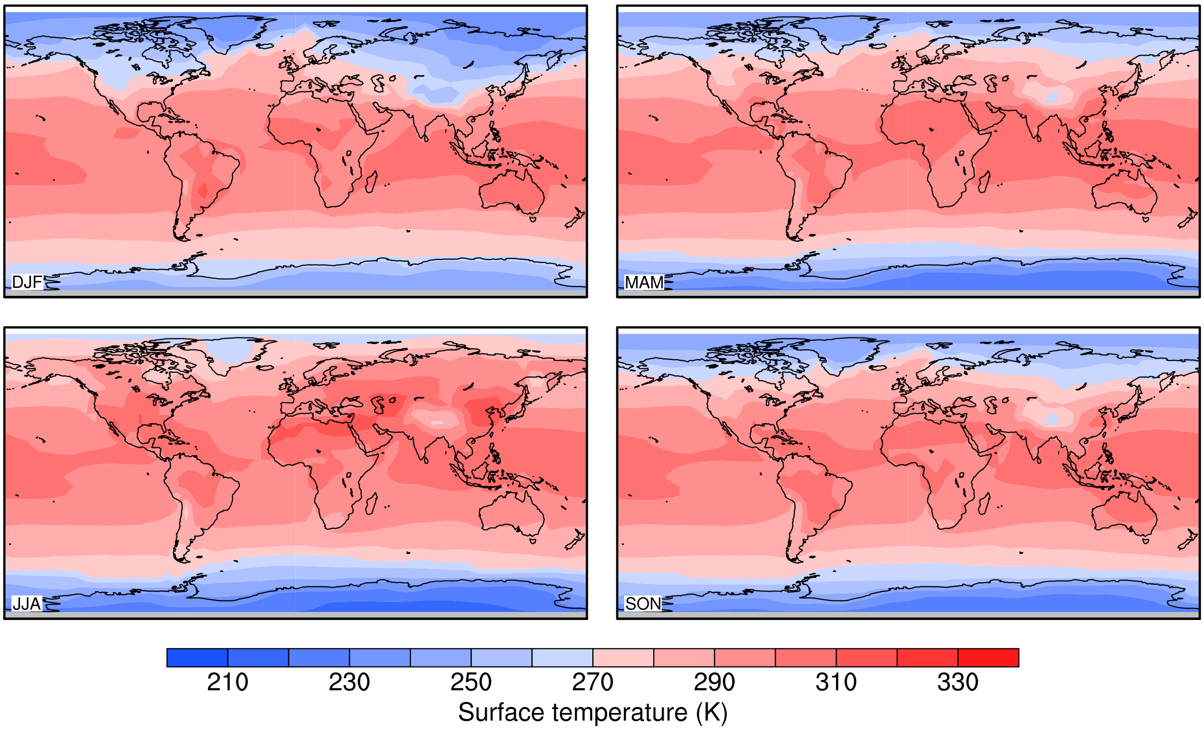


Figure 2: Seasonal surface temperature for ECBILT Experiment #1.

first Poisson filled, regridded and masked to generate a monthly sea ice climatology on the ECBILT grid. Next, some simple heuristics are used to determine "birth" and "death" months for sea ice in each grid cell, and this information is encoded into the ASCII file format used by ECBILT.

### 3.2 Model performance

The 100-year simulation performed here took about 75 minutes (wallclock and CPU time were about the same), equating to **about 45 seconds per year of simulation**. Replacing the existing LW radiation scheme in ECBILT with the more explicit scheme in the LOVECLIM code will probably slow this down a little bit, but not much.

The ECBILT code is all serial, so there may be opportunities for parallelisation if performance is a problem. The atmosphere runs at a longitude/latitude resolution of 64 × 32 using a spectral method for stepping the dynamics. I've not yet done any profiling to determine where the best places to look for optimisations are, but that would be the obvious thing to do.

### 3.3 Model climatology

Figures 2–7 show seasonal climatologies of surface temperature, precipitation, evaporation, $P - E$ and atmospheric circulation for the ECBILT Experiment #1 simulation – these should be compared with the HadAM3 HadAM3 `tcszd` simulation results in Figures 22–27 in Appendix A.

**Surface temperature** The large-scale patterns of surface temperature field in the ECBILT simulation are pretty good. Because of the SST forcing, it's a relatively easy field to get right, but it does show that there are no gross problems with the model. What differences there are between the ECBILT and HadAM3 fields appear mostly to be due to the rougher orography in ECBILT – the Tibetan plateau and western North America near the Rockies are the areas where this is most obvious.

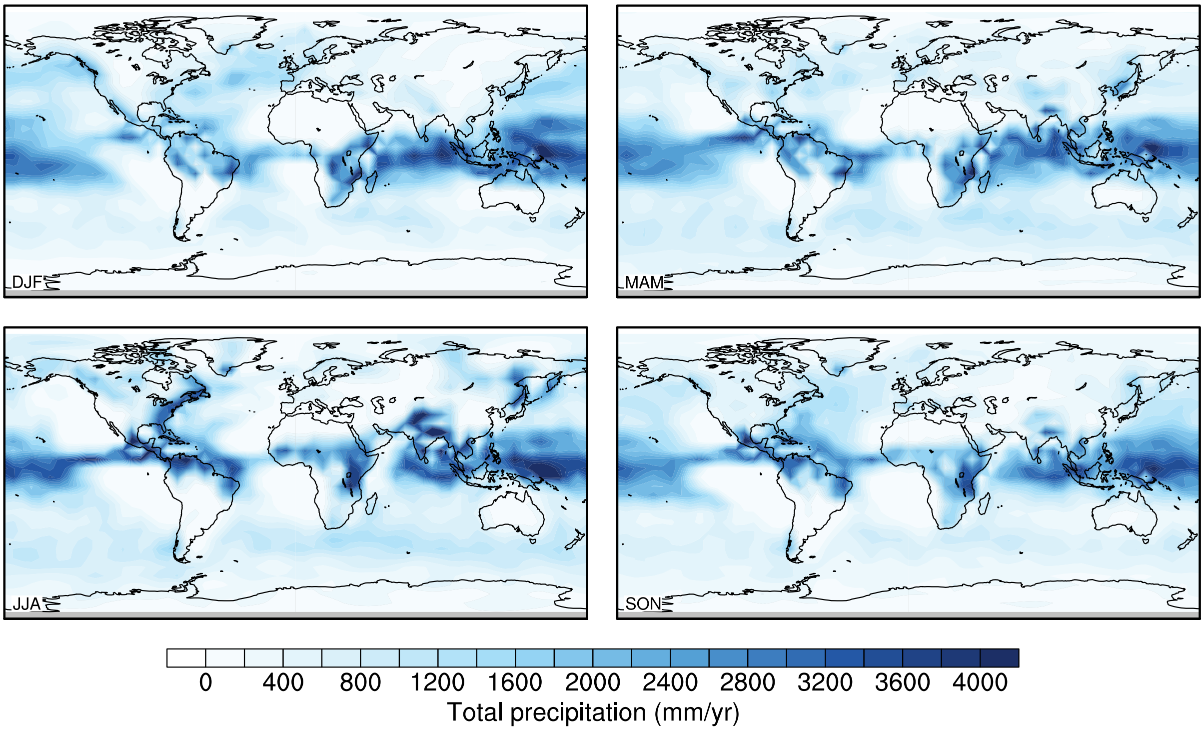


Figure 3: Seasonal precipitation for ECBILT Experiment #1.

**Precipitation** The differences between the ECBILT and HadAM3 fields here are more or less what you would expect from a comparison between a lower resolution (in both the horizontal but also, more importantly, in the vertical direction) and a higher resolution model. Winter storm tracks in the Atlantic are not well represented in ECBILT and tropical convective precipitation is much less well localised in ECBILT, with a large diffuse region of precipitation stretching from the western into the central Pacific. HadAM3 shows tropical precipitation much more localised over the western Pacific warm pool and narrow bands either side of the equator across the rest of the Pacific. These kinds of deficiencies in precipitation modelling are kind of inevitable in a model with only three levels in the vertical.

**Evaporation** Similar comments apply here as to the precipitation comparison: evaporation from the ocean is much less well spatially localised in ECBILT, with a large region of the western Pacific showing high evaporation values and no clear ITCZ being visible. Again, hard to get this right even in a model with more levels in the vertical, let alone one with only three!

$P-E$ The spatial patterns of $P-E$ in ECBILT exhibit the same problems seen in the individual precipitation and evaporation plots: the hydrological cycle is generally much more spatially diffuse than in the HadAM3 simulation (and in reality). For both models, the mean annual hydrological cycle is more or less balanced (for HadAM3 the area-averaged annual imbalance is about $-2$ mm and for ECBILT it's about 23 mm). The patterns of $P-E$ in ECBILT are weaker and more diffuse than HadAM3, although if you squint a little, the spatial patterns of positive and negative moisture budget are more or less right.

**Winds** Finally, the distribution of upper and lower level winds and vertical pressure velocity follow more or less the pattern that you would expect: the atmospheric circulation in ECBILT is weaker and more diffuse than in HadAM3, particularly in the vertical direction. This vertical smoothing because

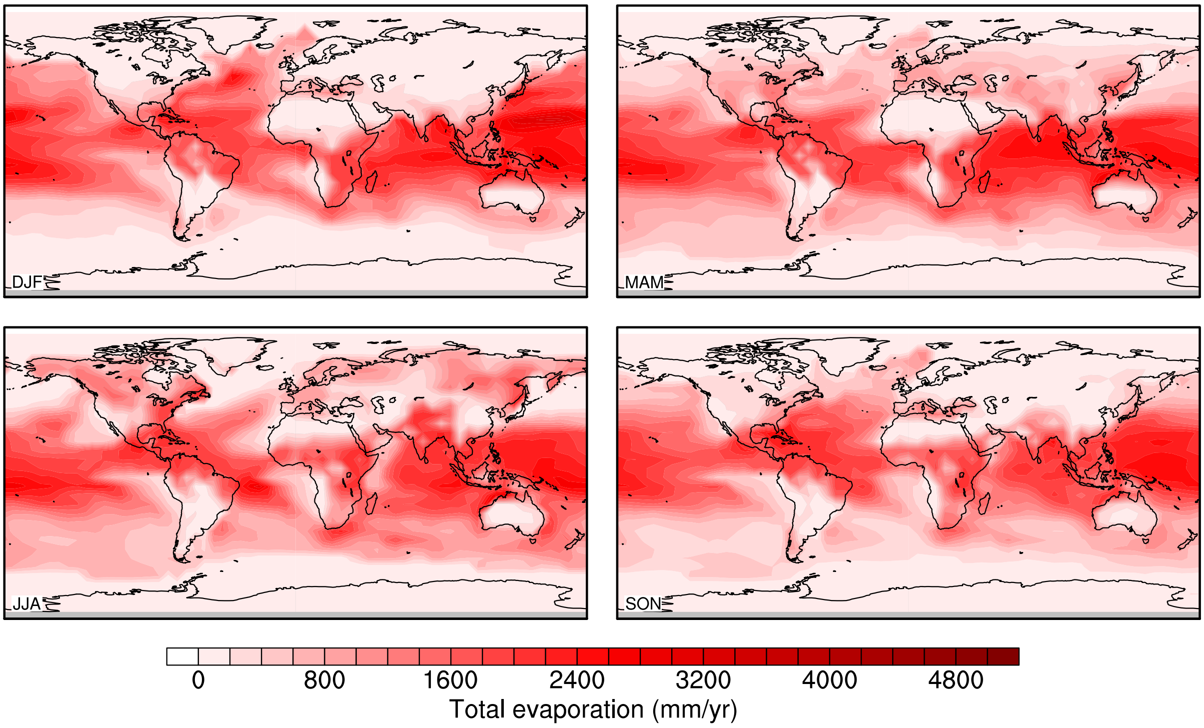


Figure 4: Seasonal evaporation for ECBILT Experiment #1.

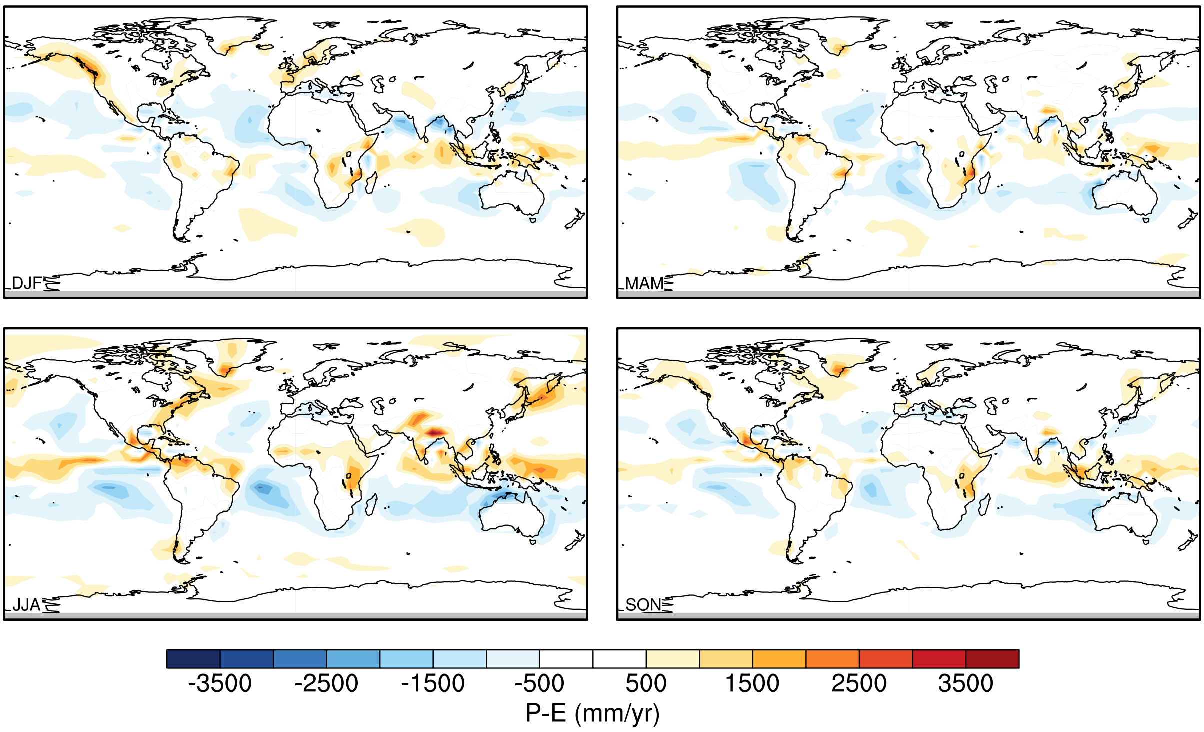


Figure 5: Seasonal precipitation minus evaporation for ECBILT Experiment #1.

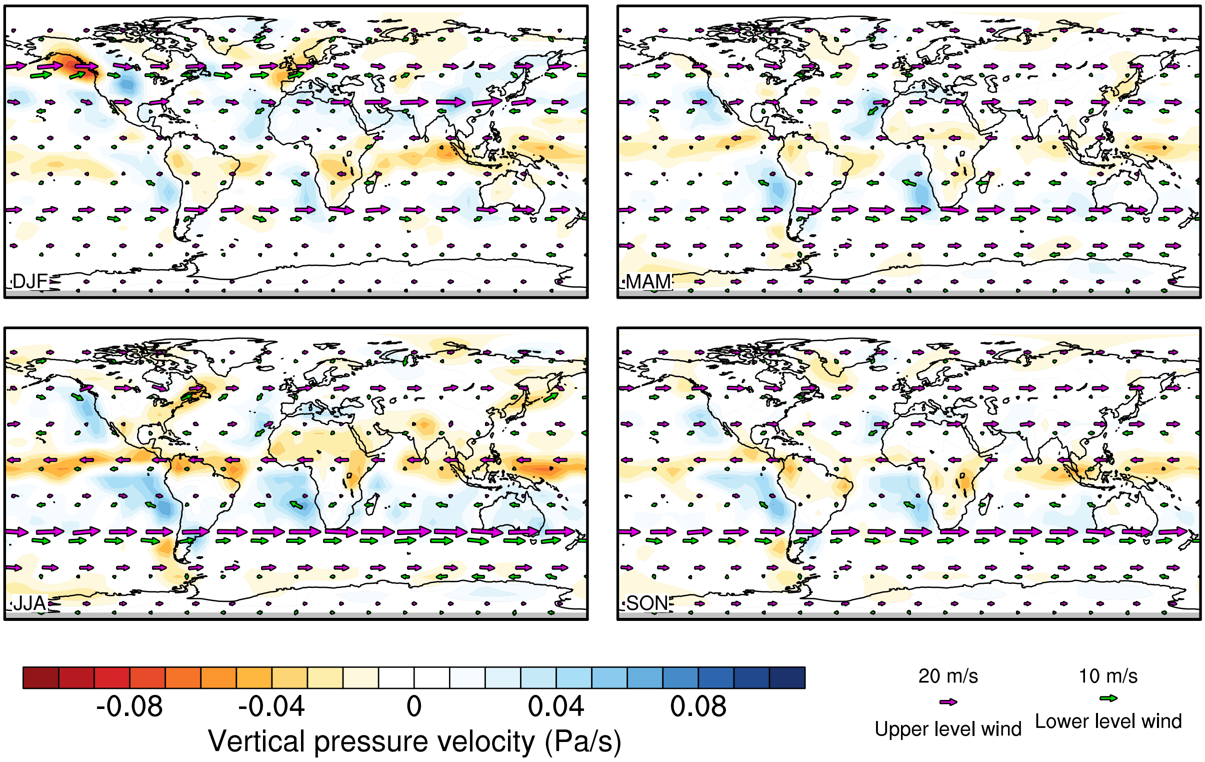


Figure 6: Seasonal circulation plots for ECBILT Experiment #1: arrows show upper level and lower level winds, colours show middle atmosphere vertical pressure velocity.

of the small number of vertical levels in ECBILT is almost certainly the source of the weaker hydrological cycle seen in the $P - E$ plots. Slightly surprisingly though, the spatial patterns and magnitude of the wind stress look pretty good, especially over the oceans.

# 4 Experiment #2

- Run name: `expt-2`.
- Original standalone ECBILT code, with only minimal changes for compilation.
- Land/sea mask, orography, SST and sea-ice forcing converted from UM `tcszd` experiment.
- River routing mask converted to new land/sea mask by hand.
- Original ECBILT albedo data: the albedo code uses a simple interpolation scheme based on fixed latitude-dependent values read in at startup for bare-soil, TOA and ocean albedo. This will need to be modified to calculate albedos based on land surface characteristics.
- Simulation length: 100 years; spin-up: 70 years; analysis: 30 years.

## 4.1 Boundary conditions

### 4.1.1 Land/sea mask and orography

For this experiment, as well as using the HadAM3 `tcszd` SST and sea-ice forcing, the model land/sea mask, orography and river routing were adapted based on the HadAM3 input data. Figure 8 shows the ECBILT land/sea mask and orography derived by regridding the HadAM3 orography with the original HadAM3 data shown alongside for comparison.

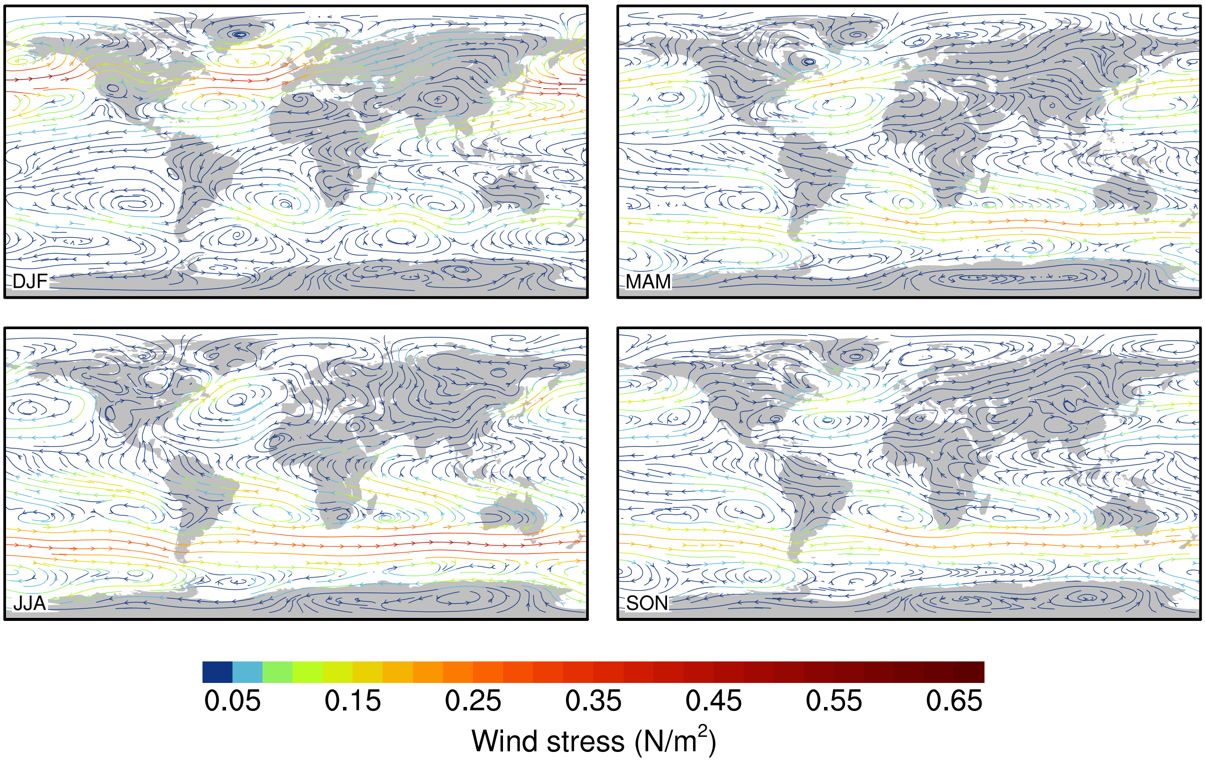


Figure 7: Seasonal surface wind stress plots for ECBILT Experiment #1.

As well as a land/sea mask, ECBILT also makes use of a lake mask – this simply masks areas of water that are not included in the land/sea mask. In this case, all land/sea contrasts are already included in the input land/sea mask derived from the HadAM3 data, so a dummy “do nothing” lake mask is generated by hand so as not to disrupt the ECBILT input data processing.

#### 4.1.2 River routing

Since the land/sea mask was changed from the ECBILT default for this experiment, it was also necessary to change the river routing maps used for diverting runoff on land to the coasts. Figure 9 shows the original ECBILT river routing map along with the new routing map based on the HadAM3 land/sea mask, which was generated by hand-editing the original ECBILT routing map.

#### 4.1.3 SST and sea-ice

The HadAM3 `tcszd` SST and sea-ice forcing were regridded for use with ECBILT in the same way as described for Experiment #1, although using the new ECBILT land/sea mask derived from the HadAM3 `tcszd` land/sea mask.

### 4.2 Model performance

The 100-year simulation performed here took about 78 minutes, equating to **about 47 seconds per year of simulation**. The differences in the land/sea mask probably account for the small difference in timing compared to Experiment #1.

### 4.3 Model climatology

Figures 10–15 show seasonal climatologies of surface temperature, precipitation, evaporation, $P - E$ and atmospheric circulation for the ECBILT Experiment #2 simulation – these should be compared

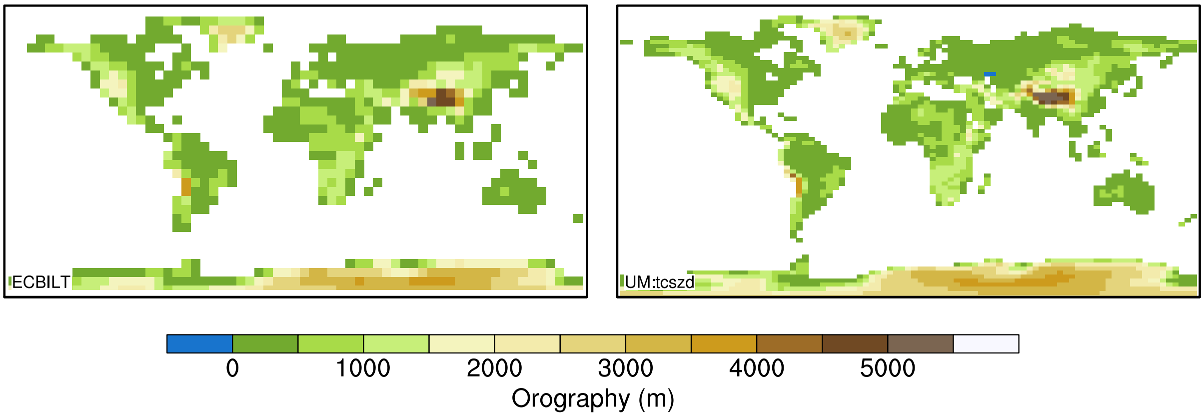


Figure 8: ECBILT and UM orography and land/sea masks used for Experiment #2.

Figure 9: River routing maps for original ECBILT land/sea mask (left) and new mask derived from HadAM3 land/sea mask (right). Lower case letters show land points composing each drainage basin, while upper case letters indicate the corresponding ocean points into which each basin drains.

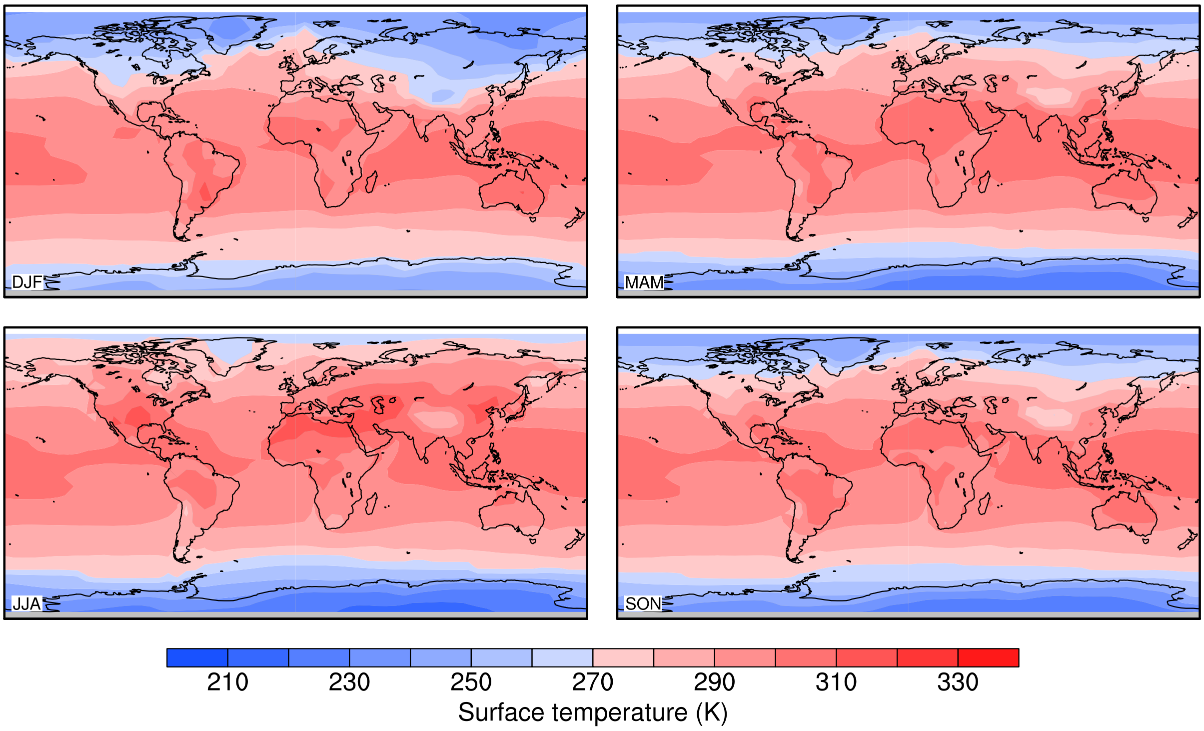


Figure 10: Seasonal surface temperature for ECBILT Experiment #2.

with the HadAM3 HadAM3 `tcszd` simulation results in Figures 22–27 in Appendix A and the Experiment #1 results in Figures 2–7.

There are small differences in all of the fields between Experiments #1 and #2, but none of these differences are very large, and all are well within the range of variability one would expect from a low-resolution model like ECBILT. The model climatology thus does not appear to be highly sensitive to the land/sea mask and river routing definitions used, which makes it reasonable to think that ECBILT should provide a reasonable climatology when run using modern-day GENIE land/sea masks and river routing information.

# 5 Experiment #3

- Run name: `expt-3`.
- LOVECLIM ECBILT code adapted to run as standalone atmosphere model.
- Boundary conditions as for Experiment #2.
- Greenhouse gas concentrations: fixed at 286.43 ppmv ($CO_2$), 796.60 ppbv (methane), 275.40 ppbv ($N_2O$); 25.0 DU (tropospheric ozone).
- Simulation length: 100 years; spin-up: 70 years; analysis: 30 years.

## 5.1 Code changes

Here, I took the ECBILT code as used in LOVECLIM and disentangled it from the LOVECLIM coupling code to make a standalone atmospheric model, replacing the CLIO ocean GCM from LOVECLIM with the fixed ocean model from the original ECBILT and replacing the VECODE dynamic vegetation model with a fixed land surface scheme.

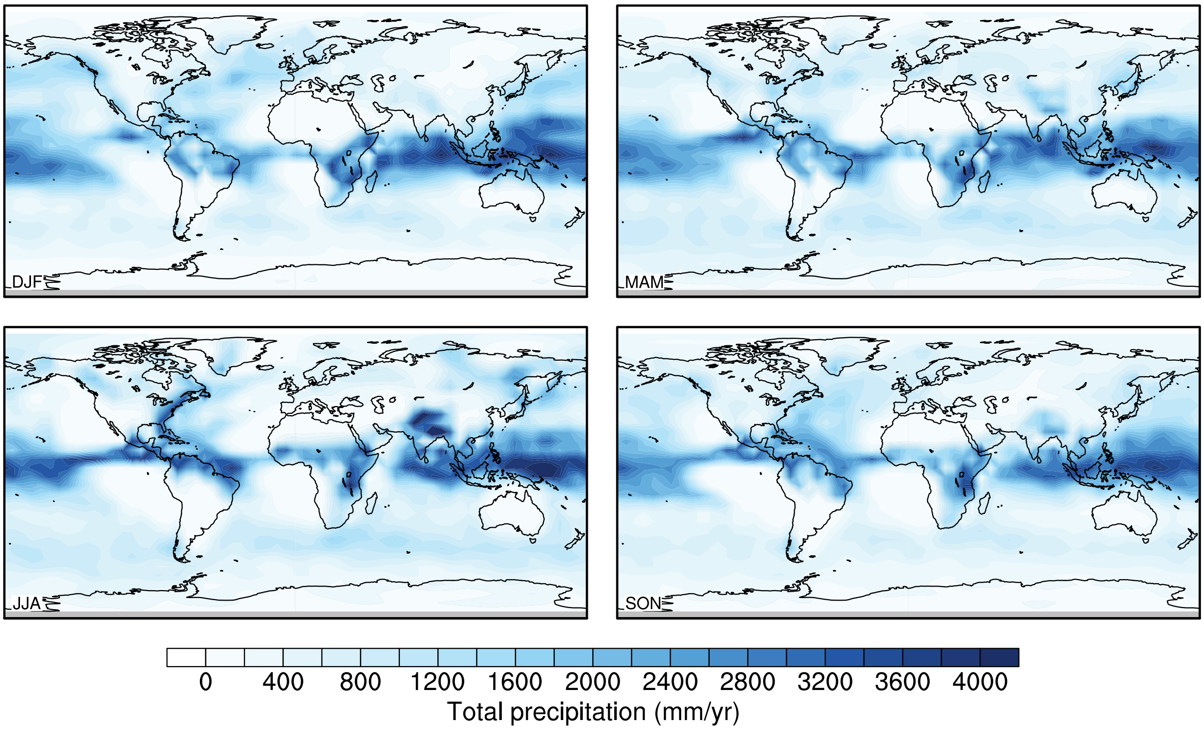


Figure 11: Seasonal precipitation for ECBILT Experiment #2.

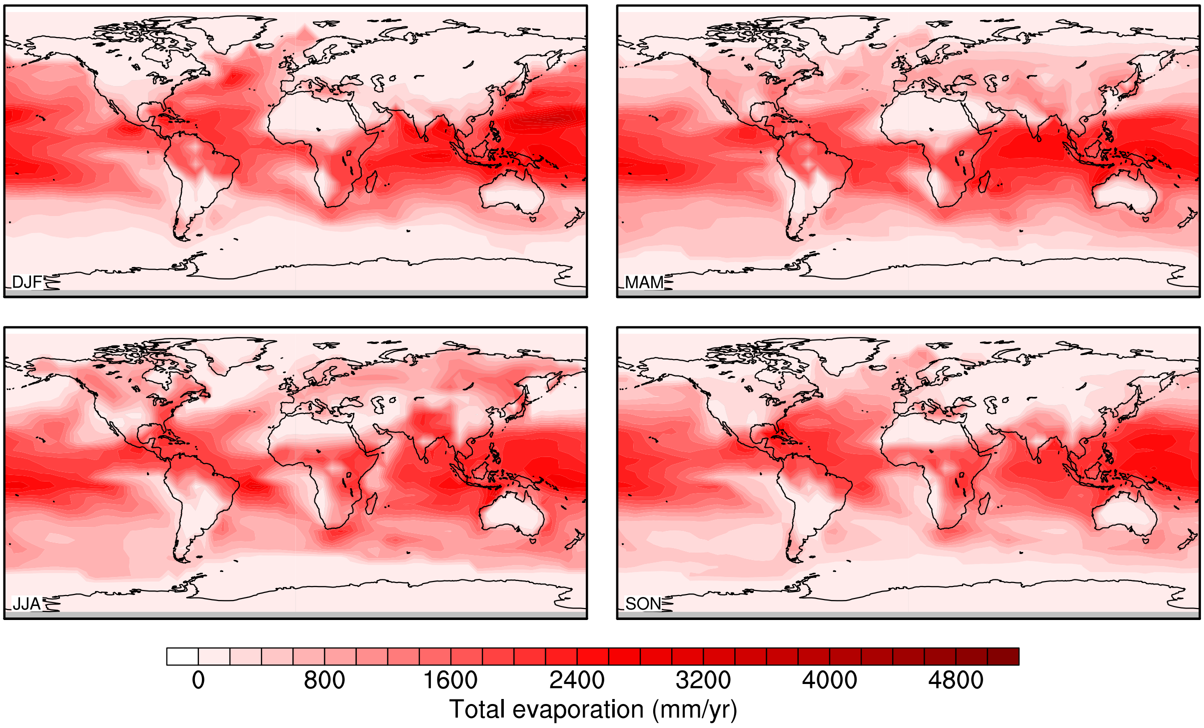


Figure 12: Seasonal evaporation for ECBILT Experiment #2.

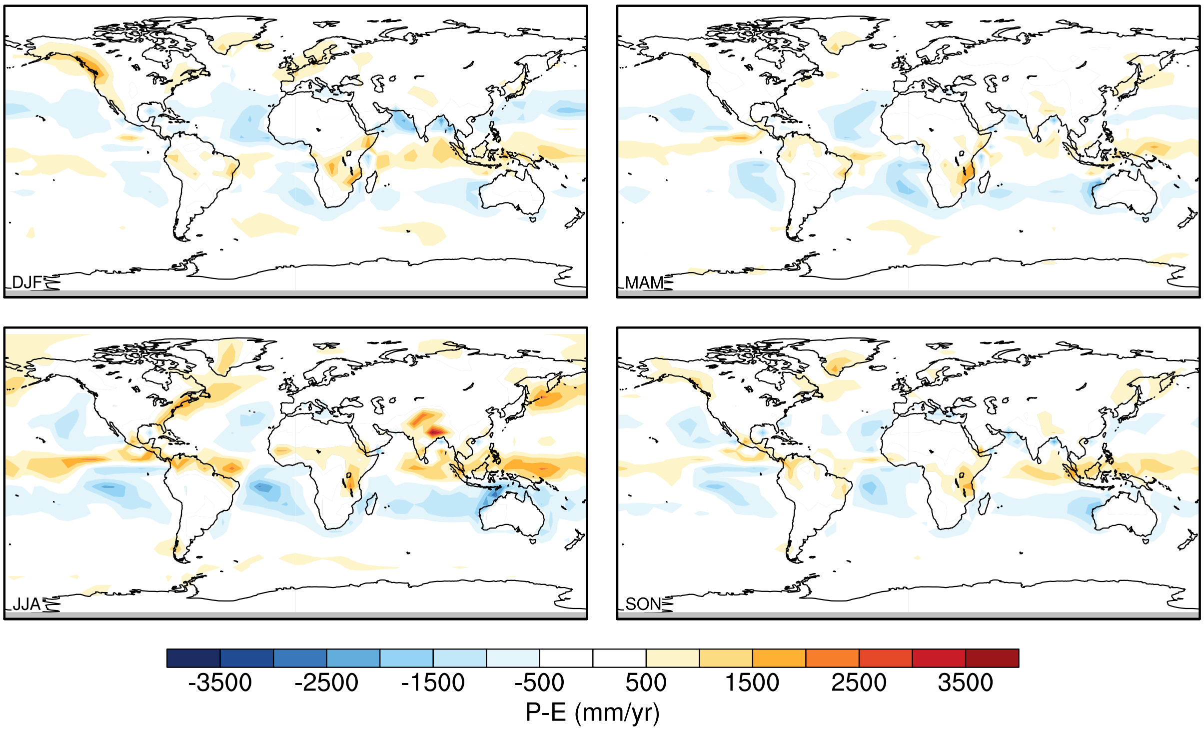


Figure 13: Seasonal precipitation minus evaporation for ECBILT Experiment #2.

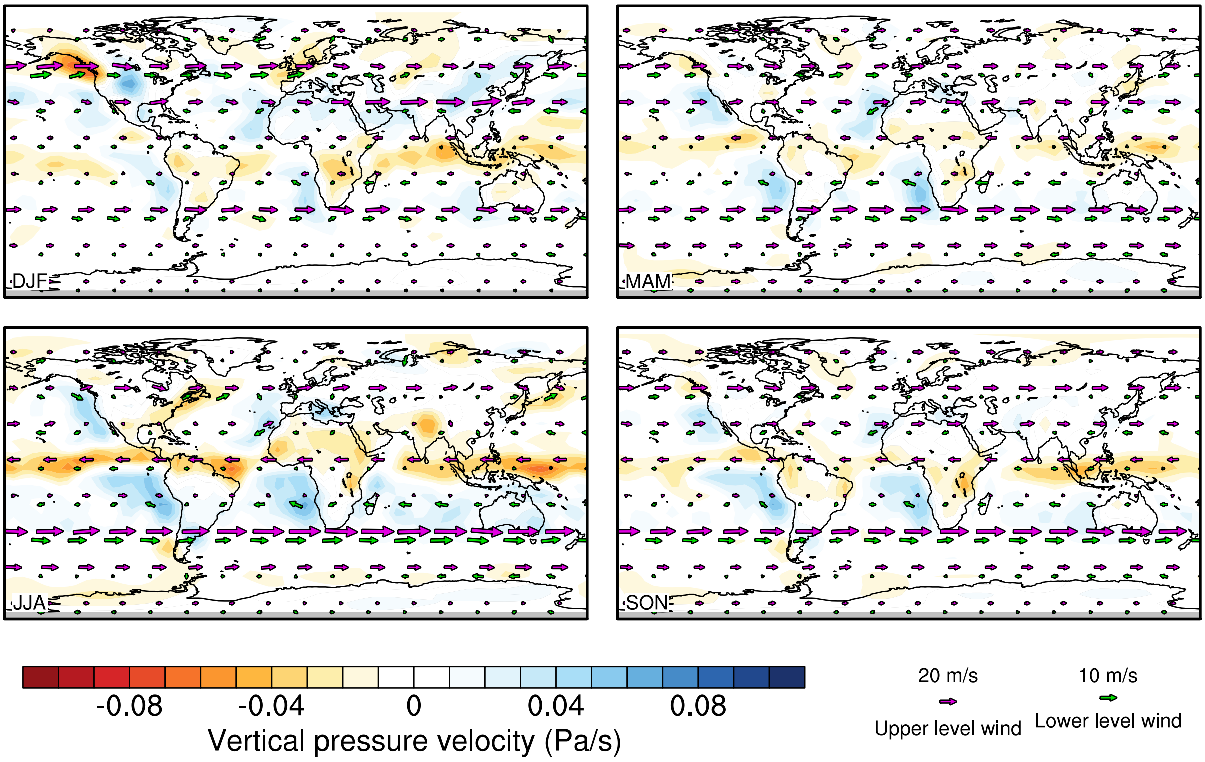


Figure 14: Seasonal circulation plots for ECBILT Experiment #2: arrows show upper level and lower level winds, colours show middle atmosphere vertical pressure velocity.

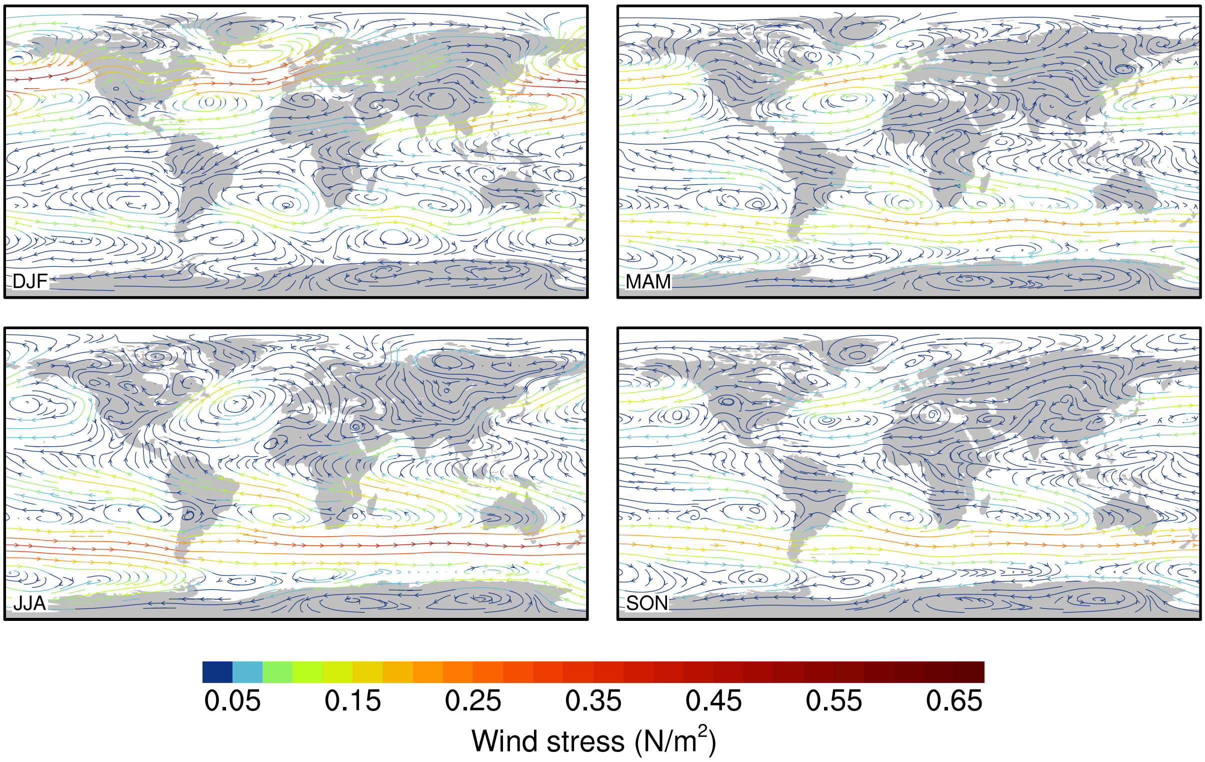


Figure 15: Seasonal surface wind stress plots for ECBILT Experiment #2.

To do this, I vastly simplified the original LOVECLIM model configuration and build process to have a standalone "Fortran + makefiles" setup for building ECBILT. I stubbed out all of the LOVECLIM-related coupling code, then added back the fixed ocean and land surface from the original ECBILT bit-by-bit. After getting all this to build, I did a bit of tidying up then reorganised all the boundary condition file handling to make setting up experiments simpler.

The standalone atmosphere model didn't work right away. There were a couple of problems that meant I had to make some model changes, and they both required quite a bit of time to track down:

1. I had to fix the calculation of horizontal moisture diffusion, which had changed from the original ECBILT code and led to all sorts of numerical problems and completely unrealistic looking moisture fields. I have no idea at all how this ever worked in LOVECLIM since the equation for the diffusion was missing some essential scaling constant. Perhaps the moisture field was corrected somewhere else in the coupled model? I could never track down what was happening, but reverting to the moisture diffusion calculation from the original ECBILT made the problems go away.

2. I have to clamp sea ice temperature to a minimum value of 200K K. The LOVECLIM ECBILT radiation and atmospheric temperature profile calculations are based on interpolation from reference atmospheric profiles. Some of these reference profiles have surface temperature inversions (i.e. the lowest level in the atmospheric profile is colder than higher layers), which can mess up the interpolation of temperature profiles down to the surface, producing unrealistically cold conditions in some places. The best solution to this seems just to be to clamp the temperature and prevent these cold excursions.

## 5.2 Boundary conditions

The boundary conditions used for this experiment are essentially identical to those for Experiment #2.

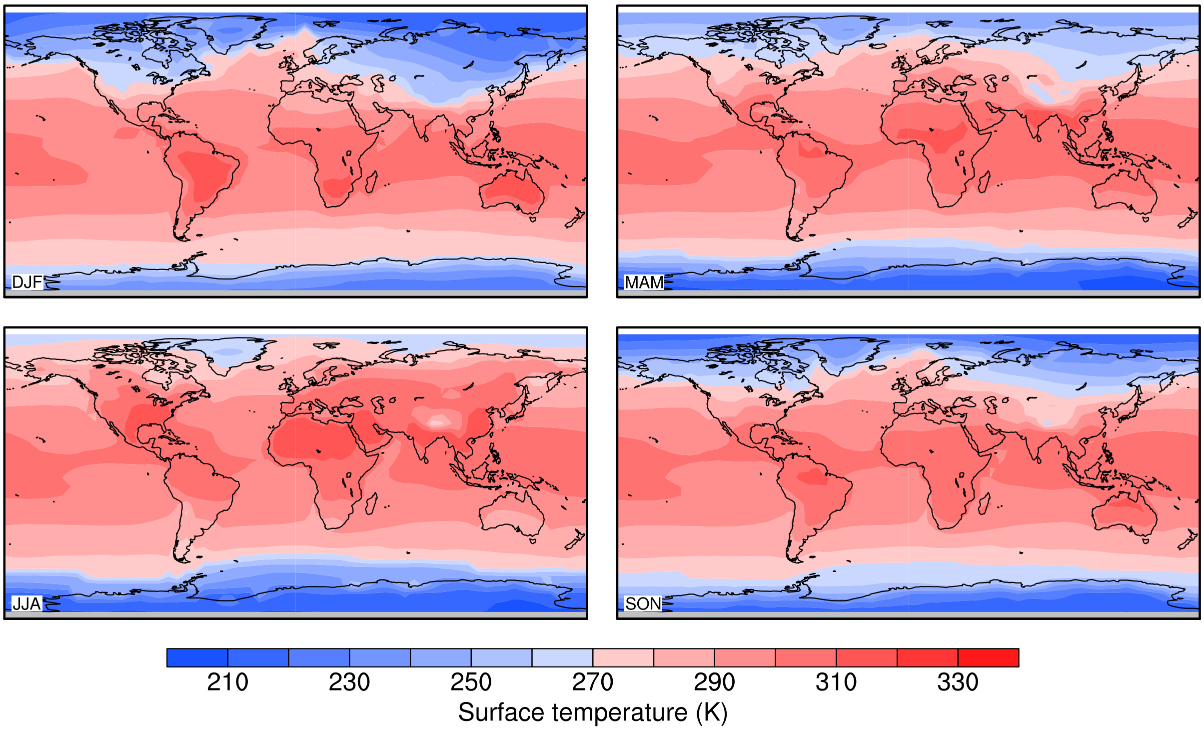


Figure 16: Seasonal surface temperature for ECBILT Experiment #3.

### 5.3 Model performance

The 100-year simulation performed here took about 58 minutes, equating to **about 35 seconds per year of simulation**. I'm not sure why the timing here is so different from Experiment #2.

### 5.4 Model climatology

Figures 16–21 show seasonal climatologies of surface temperature, precipitation, evaporation, $P-E$ and atmospheric circulation for the ECBILT Experiment #3 simulation – these should be compared with the HadAM3 HadAM3 `tcszd` simulation results in Figures 22–27 in Appendix A and the Experiment #2 results in Figures 10–15.

These initial results don't look all that great – the following problems can be identified immediately:

- The polar regions seem to be very cold. This may be related to the problems with reference atmospheric profiles described above.
- There seems to be something wrong with the land surface scheme, since there's no evaporation occurring over the land.
- The winds are generally too weak, and wind stress in the Southern Ocean is very weak indeed in the southern summer.

That said, the $P-E$ pattern looks better than for the other ECBILT simulations, and the atmospheric circulation really isn't all that bad for a first set of simulations with a new model setup.

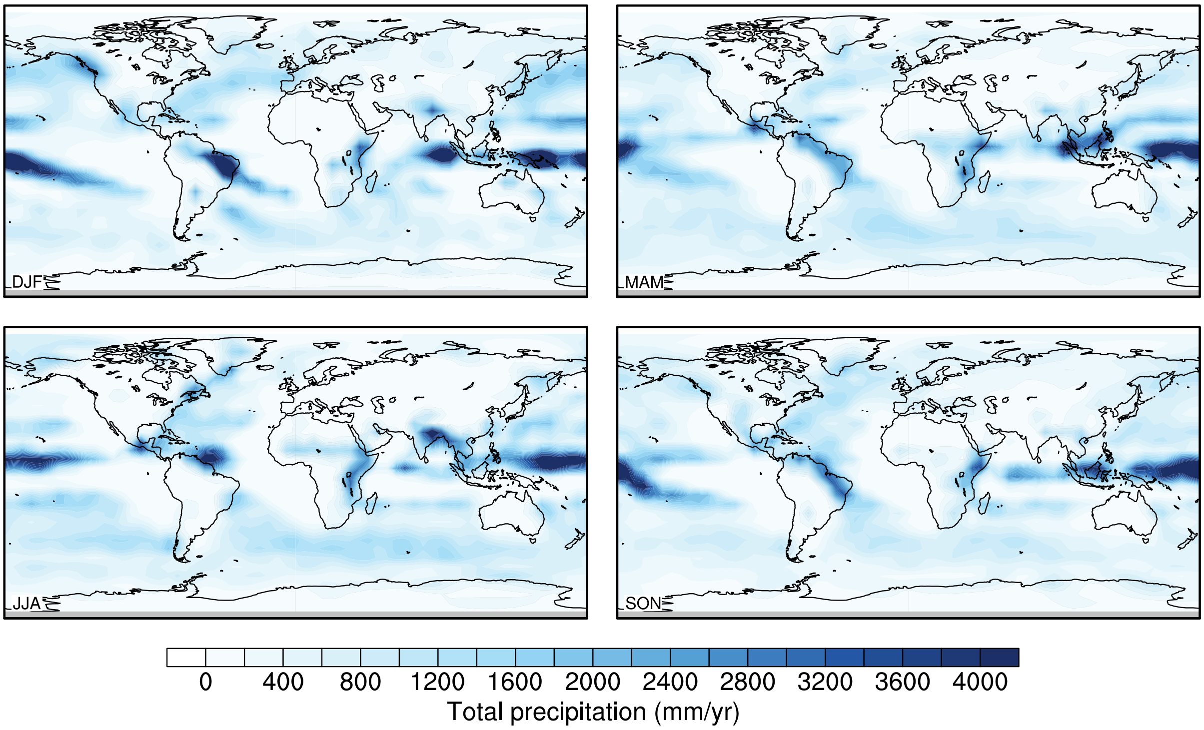


Figure 17: Seasonal precipitation for ECBILT Experiment #3.

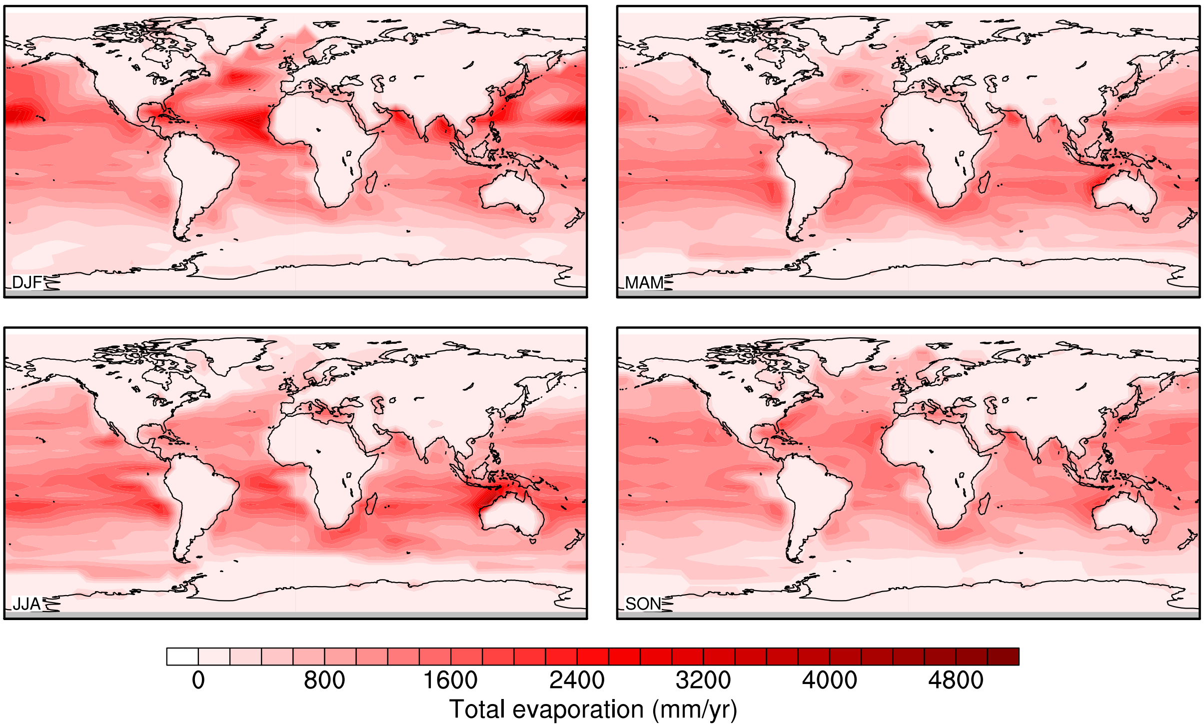


Figure 18: Seasonal evaporation for ECBILT Experiment #3.

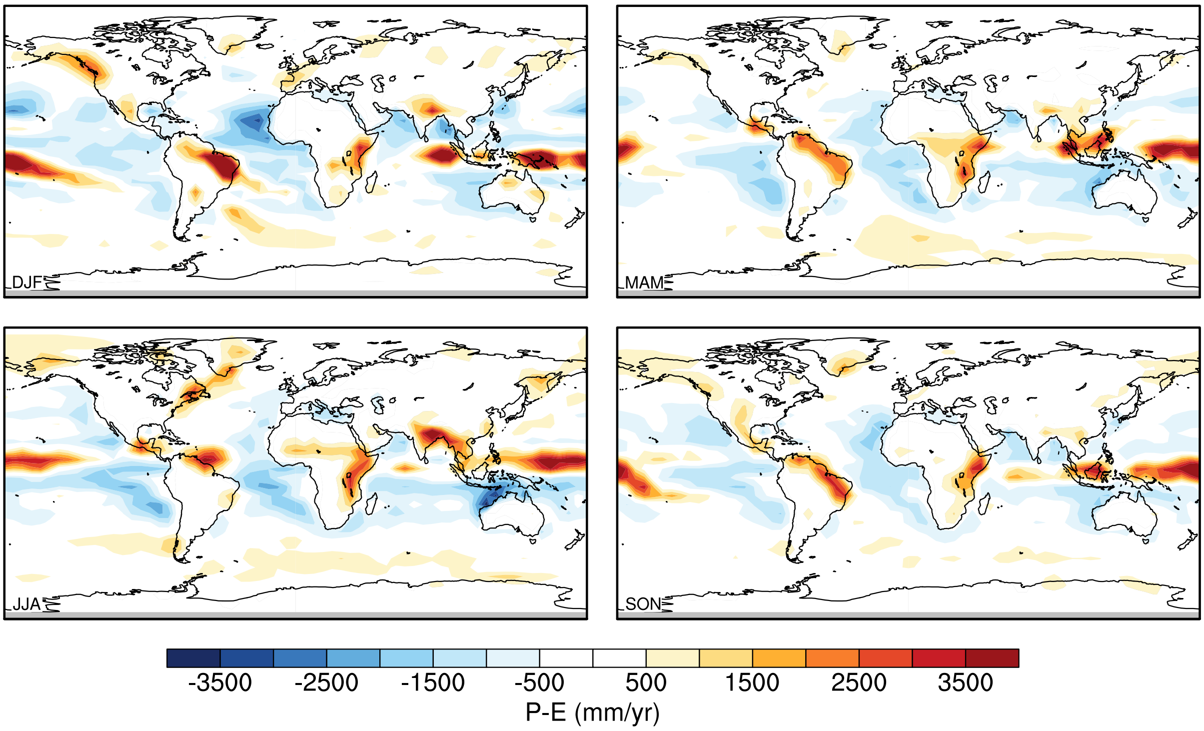


Figure 19: Seasonal precipitation minus evaporation for ECBILT Experiment #3.

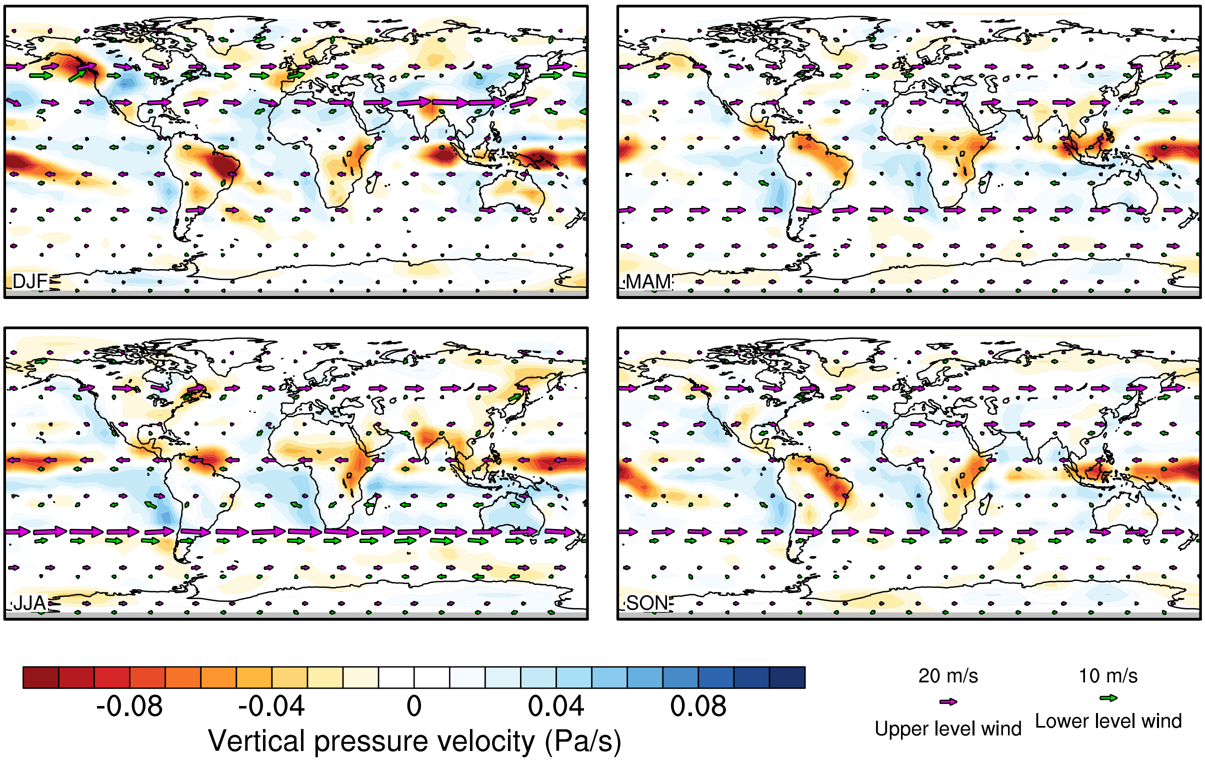


Figure 20: Seasonal circulation plots for ECBILT Experiment #3: arrows show upper level and lower level winds, colours show middle atmosphere vertical pressure velocity.

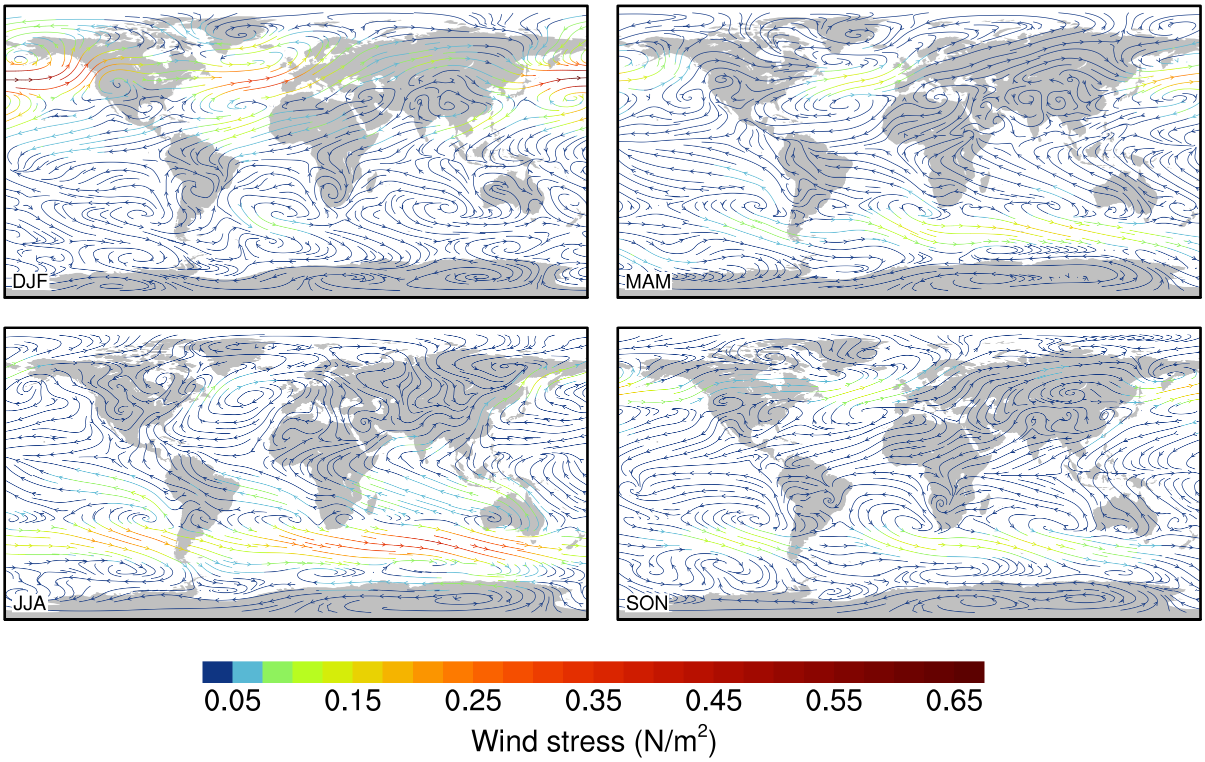


Figure 21: Seasonal surface wind stress plots for ECBILT Experiment #3.

# 6 ECBILT/GENIE compatibility

## 6.1 Code compatibility

The notes here are based on a comparison between the ECBILT code and the existing EMBM atmosphere model within GENIE.

**Model initialisation** This should be straightforward. Both EMBM and ECBILT read a range of model parameters from files during initialisation (as well as initial atmospheric state), and only a little reorganisation of the ECBILT code would be required. One more significant change that it might be worth making is to reorganise the ECBILT input files to use NetCDF format files instead of the range of custom binary formats currently used. This would make the initialisation files portable between machines of different endianness.

**Model timestepping** In principle, this also ought to be easy to do – GENIE uses a single function call to step that atmosphere along one timestep, and it should be straightforward to wrap all of the ECBILT timestepping functionality up into a single routine in that way. Mismatches between the GENIE timestep and the ECBILT timestep can be dealt with by performing multiple ECBILT steps for each GENIE step. Any differences between EMBM and ECBILT in terms of the forcings required from the ocean model can be modified in the wrapper function that calls the atmosphere model (there shouldn't be any changes here: surface radiation and moisture fluxes should be all that's needed).

**Model coupling** The ECBILT atmosphere uses a $64 \times 32$ Gaussian grid, so there may need to be some regridding of fields to and from the regular GOLDSTEIN grid. That shouldn't be a problem.

### 6.2 Model parameterisation issues

At least one aspect of ECBILT that I've identified may cause trouble – it uses an empirical fit to modern atmospheric profiles for its radiation and atmospheric energy balance (i.e. atmospheric temperature profile calculation) schemes. This is true both for the "original" ECBILT and the modified version incorporated in LOVECLIM. At startup the model reads in atmospheric profiles and associated radiation coefficients based on (for the LOVECLIM model) the NCEP atmospheric reanalysis split by region of the globe (including special profiles for some mountain regions), or (for the "original" model) simulations using a version of the GFDL AGCM. This dependence on parameterisations based on modern atmospheric profiles obviously isn't appropriate for deep paleo simulations where the distribution of land and ocean is different to modern conditions.

As far as I can tell from a quick search in the literature, the LOVECLIM EMIC has been used for simulations only as far back as 800 ka (and that was only one paper – most applications were more recent) so this wasn't really a problem before.

Another quick literature survey indicates that there probably aren't any other EMICs that have been used for paleo simulations that contain a "real" atmospheric GCM: the UVic and McGill models and the CLIMBER models all use statistical dynamical "2.5D" atmosphere models. The only "3D" GCM that's been coupled into an EMIC seems to be IGCM in GENIE... IGCM does have a "proper" radiation scheme based on band absorption coefficients for a selection of absorbing gases, i.e. it's more or less a "first principles" radiation scheme, with no dependence on parameterisation based on atmospheric profiles.

I don't know whether it would be practical to transplant the IGCM radiation scheme into ECBILT. From a survey of the IGCM code, it certainly looks possible, but I have no idea whether it would work (IGCM has seven or eight levels in the vertical, ECBILT only three, which might screw things up), and I have no idea how much it would slow ECBILT down – some of the radiation calculations look like they might be quite onerous.

It's certainly possible that there may be other things like this hiding within the ECBILT code, but so far the radiation scheme seems like the biggest impediment.

## A HadAM3 `tcszd` comparison results

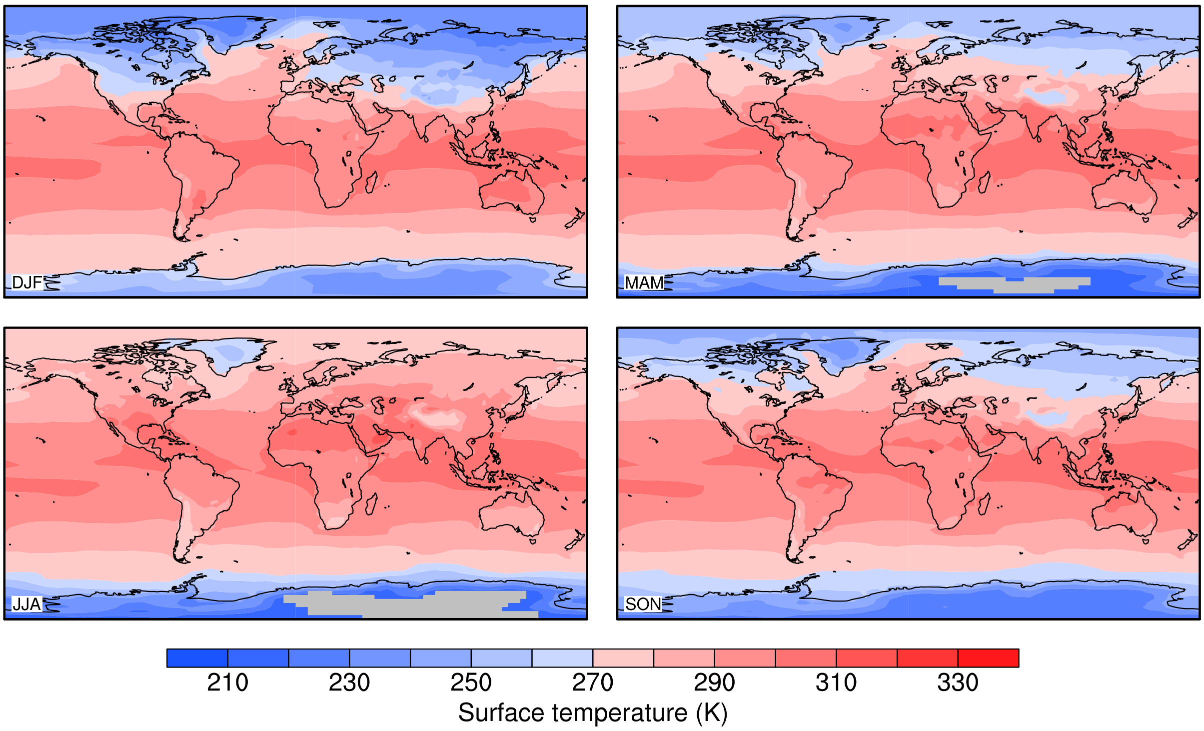


Figure 22: Seasonal surface temperature for HadAM3 `tcszd` comparison simulation.

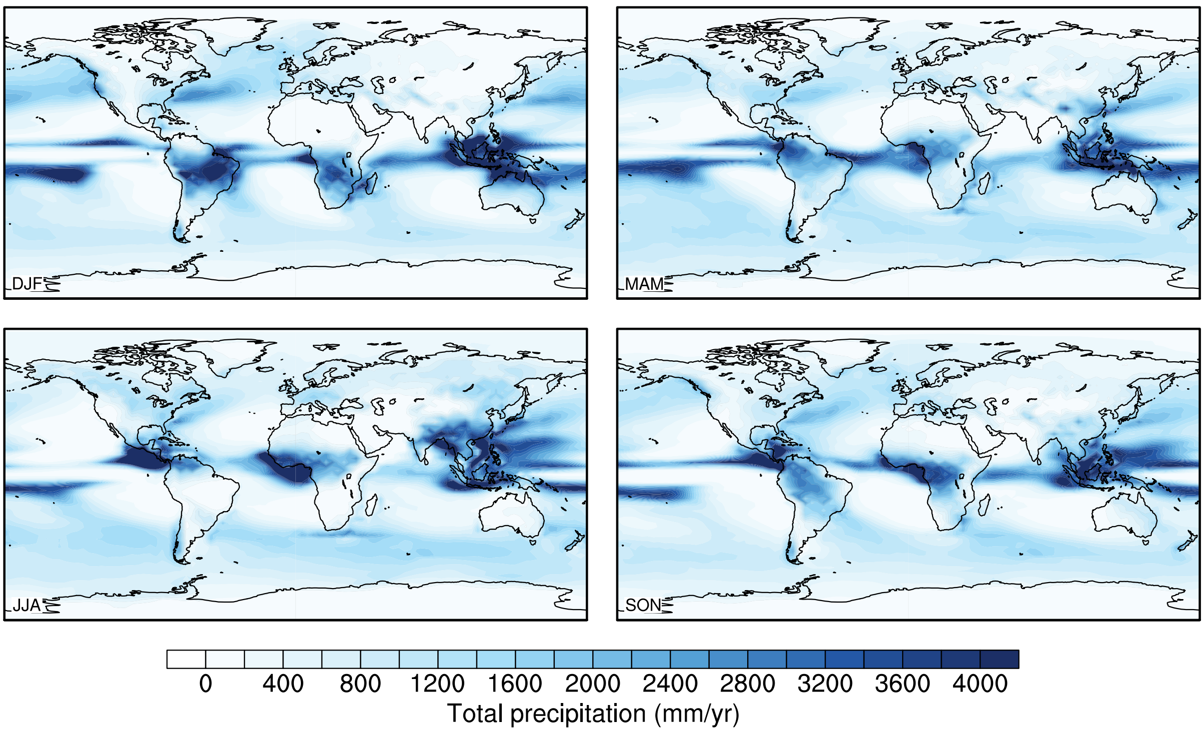


Figure 23: Seasonal precipitation for HadAM3 `tcszd` comparison simulation.

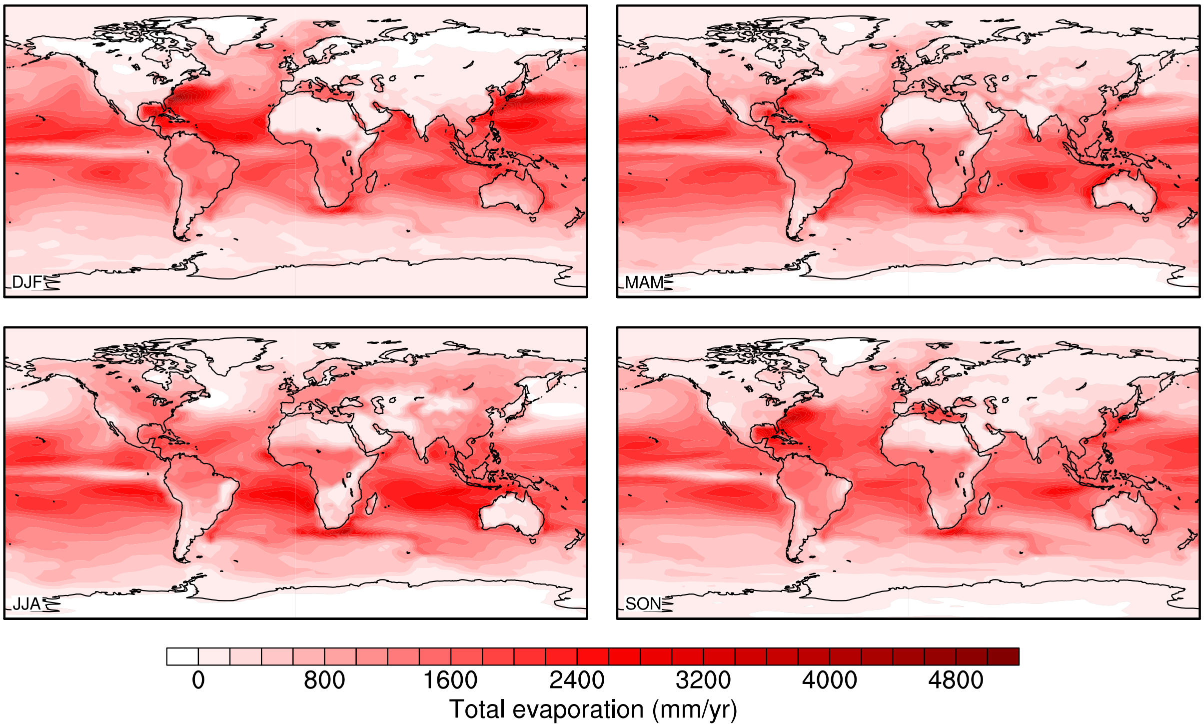


Figure 24: Seasonal evaporation for HadAM3 `tcszd` comparison simulation.

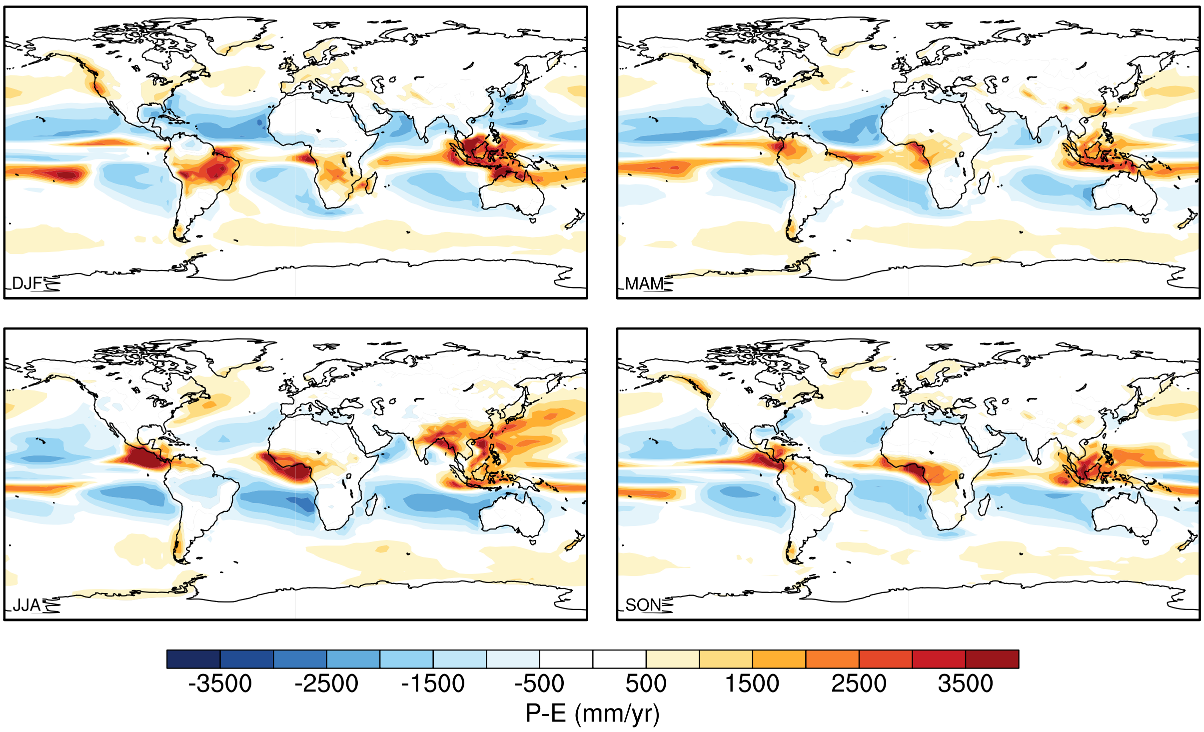


Figure 25: Seasonal precipitation minus evaporation for HadAM3 `tcszd` comparison simulation.

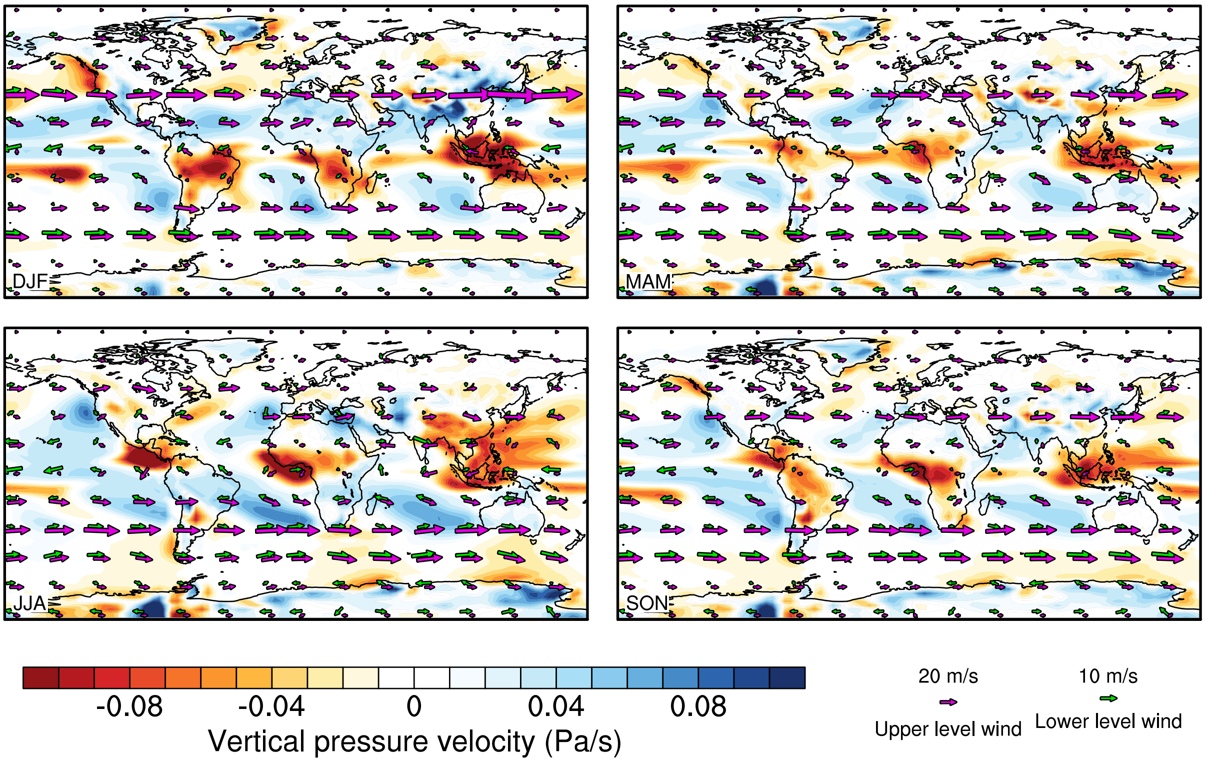


Figure 26: Seasonal circulation plots for HadAM3 `tcszd` comparison simulation: arrows show upper level and lower level winds, colours show middle atmosphere vertical pressure velocity.

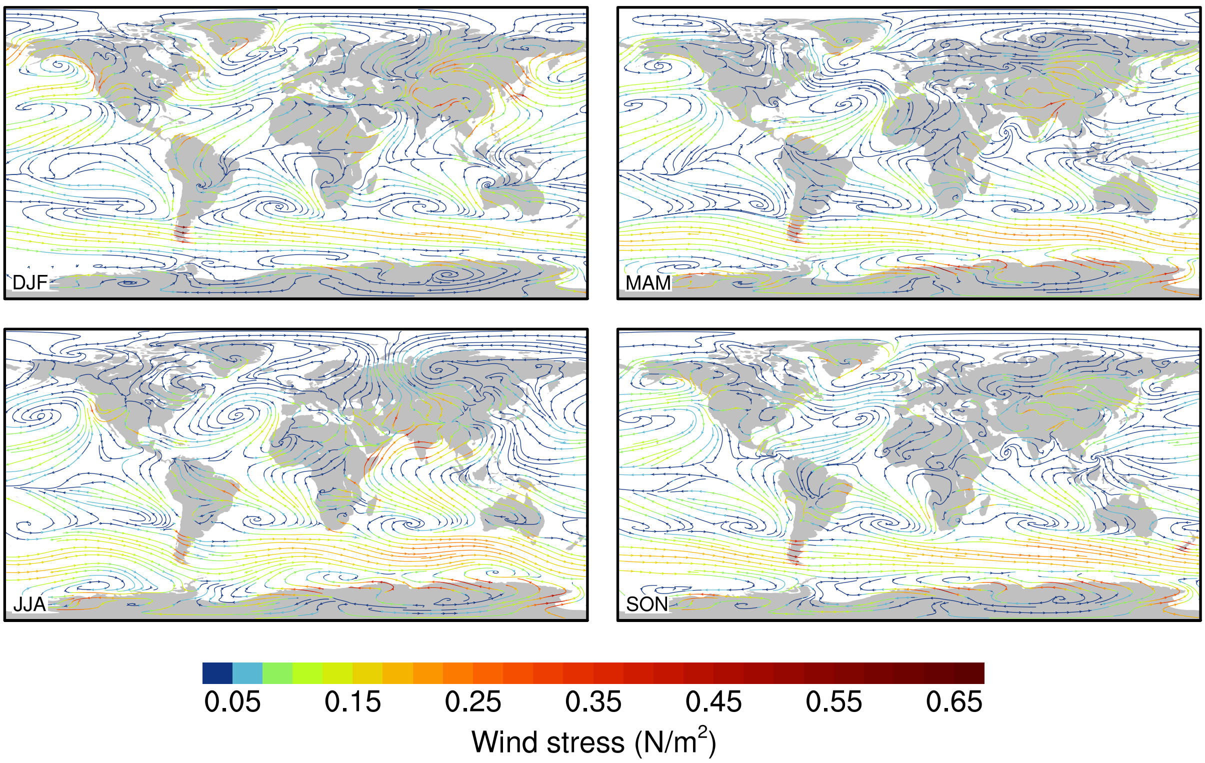


Figure 27: Seasonal surface wind stress plots for HadAM3 `tcszd` comparison simulation.