Technical documentation of the MESSy submodel VERTDIFF (MESSy version 2.50+ and beyond)

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1 Introduction

The current suite of MESSy physical parametrization submodels does not include a submodel for vertical diffusion. For simulations with the ECHAM5 basemodel, the ECHAM5 vertical diffusion code is called within the ECHAM5 code and not from MESSy, relying on ECHAM5 data and without strict data separation. For CESM1, the vertical diffusion is part of the CAM parametrization suite. Since this is not called in CESM1/MESSy simulations, the vertical diffusion code of CAM was restructured as a MESSy submodel.

So far, the implementation only encompasses the dry turbulence scheme from Holtslag and Boville (1993), which is the default turbulence scheme in CAM3 and CAM4. CAM5 offers a new moist turbulence scheme, discussed in Bretherton and Park (2009), which is not implemented in the MESSy submodel yet.

2 Submodel features

The new submodel VERTDIFF

1. calculates the surface drag coefficient k_{tns} and wind stress associated with subgrid mountains (optional),
2. calculates the mixing coefficients (diffusivities) in the free troposphere based on the gradient Richardson number. The diffusivity K_c is calculated as

   $$K_c = l_c^2 S F_c(Ri), \tag{1}$$

   where S is the local shear, l_c is the mixing length, which is a function of the Von Karman constant and the asymptotic length scale, taken to be 30 m above the PBL. F_c is a stability function and depends on the Richardson number. Note that this approach assumes that the length scale of the largest turbulent eddies is smaller than the size of the domain over which the turbulence extends. For more details see the documentation of CAM4[1], section 4.11.1, also discussed by Jacobson (2005), section 8.5.1. In comparison, ECHAM5 uses a similar approach but the asymptotic length scale is decreased exponentially with height.
3. calculates the mixing coefficients (diffusivities) associated with turbulence in the planetary boundary layer (PBL), based on Holtslag and Boville (1993), using an explicit, non-local PBL parameterization. The above assumption for small enough length scales is violated in unstable and convective conditions, where the largest transporting eddies may have a size similar to the PBL height itself, and the flux can be counter to the local gradient. In this case, the eddy diffusivity is better represented with turbulent properties characteristic of the PBL ("non-local diffusion"). The eddy diffusivity K_c for heat, water vapor, and passive scalars is then given by

   $$K_c = k w_t z \left(1 - \frac{z}{h}\right)^2, \tag{2}$$

   where w_t is a turbulent velocity scale, h is the boundary layer height, z is geopotential height, and k is the Von Karman constant. For momentum, the velocity scale is replaced by another scale. A detailed description is given at CAM4, 4.11.2.

[1] http://www.cesm.ucar.edu/models/ccsm4.0/cam/

4. applies a tri-diagonal solver for the vertical diffusion equations to calculate the diffusivities as well as the non-local transport terms. Countergradient fluxes are also applied. The solution is obtained using an implicit backward Euler scheme, see eq. 4.30 in the CAM5 documentation[2]. Again, a full discussion is given in the CAM4 description, sections 4.11.3 and 4.11.4.

5. calculates implicit surface stress (optional). The surface stress (or momentum flux) τ_x, τ_y is added into the lowest model layer in an implicit way, in order to prevent flipping of the wind direction. For a detailed description of the technique see Sect. 4.2.9 in the CAM5 documentation. Note that the surface stress (or momentum flux) τ_x, τ_y, the sensible heat flux, and the surface evaporation water flux are calculated by the land model.

3 SMIL

All calculations required in the time loop are perfomed in the `messy_vdiff` main entry point. In the SMIL subroutine `vertdiff_cam_vdiff`, the following steps are performed:

1. estimate the updated temperature, winds, specific humidity, and cloud ice and water
2. calculate static energy from temperature
3. call to turbulent mountain stress subroutine in SMCL (optional)
4. estimate saturation specific humidity (lookup table)
5. call to diffusion equation solver in SMCL
6. derive the diagnostic
   - liquid water static energy (`sl`)
   - liquid water virtual static energy (`slv`)
   - total water mixing ratio
   - zonal and meridional momentum fluxes
   - liquid static energy flux
   - total water flux
7. calculate tendencies from integrated values for wind, specific humidity, cloud liquid and ice, tracers, static dry energy
8. derive the temperature tendency from the static dry energy tendency

4 SMCL

The SMCL contains the following Fortran90 modules:

`messy_vertdiff_camhbdiff` to compute mixing coefficients (eddy diffusivities and counter-gradient fluxes) associated with turbulence in the planetary boundary layer and elsewhere.

`messy_vertdiff_camtrbmtnstress` for turbulent mountain stress parameterization: calculates surface drag coefficient and stress associated with subgrid mountains.

`messy_vertdiff_camdiffsolver` to solve vertical diffusion equations using a tri-diagonal solver. Countergradient fluxes are also applied.

`messy_vertdiff_tools` provides various tools, e.g., for the calculation of saturation vapor pressure, wet bulb temperature, the Obukhov length and kinematic fluxes.

[2]http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf

5 Submodel namelist

The namelist `vertdiff.nml` (group `&CTRL_CAM`) currently offers the following options:

`eddy_scheme` (integer) can be set to “Holtslag and Boville” scheme (default, value 1) or the “Holtslag and Boville and Rash” scheme (value 2)

`do_tms` (logical) allows to turn on/off the turbulent mountain stress

`do_iss` (logical) switch for implicit turbulent surface stress

In the future, the submodel is likely to be extended by the ECHAM5 vertical diffusion scheme, therefore the submodel and namelist are already prepared for this. The group `&CTRL` will offer the possibility to choose the scheme with the variable `vdiff_scheme`.

The following provides an example namelist for the submodel.

```
&CTRL
vdiff_scheme = 1 ! vertical diffusion scheme from CAM5
/
&CTRL_CAM
! CAM5 vdiff options:
eddy_scheme  = 1  ! 1 = Holtslag and Boville (default)
!eddy_scheme  = 2  ! 2 = Holtslag and Boville and Rash
do_tms = T ! switch for turbulent mountain stress
do_iss = F ! switch for implicit turbulent surface stress
/
```

References

Bretherton, C. S. and Park, S.: A New Moist Turbulence Parameterization in the Community Atmosphere Model, J. Climate, 22, 3422–3448, doi:10.1175/2008JCLI2556.1, 2009.

Holtslag, A. A. M. and Boville, B. A.: Local Versus Nonlocal Boundary-Layer Diffusion in a Global Climate Model., J. Climate, 6, 1825–1842, doi:10.1175/1520-0442(1993)006⟨1825:LVNBLD⟩2.0.CO;2, 1993.

Jacobson, M. Z.: Fundamentals of Atmospheric Modeling, Cambridge University Press, 2nd edn., 2005.