

A Brief Introduction to SPEEDY

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SPEEDY: Simplified Parameterizations, Primitive-Equation Dynamics

*An AGCM with spectral dynamical core and modified
parameterisations*

Main developers:

Franco Molteni, ECMWF, Reading, UK.

Fred Kucharski, Abdus Salam International Centre for
Theoretical Physics, Trieste, Italy.

Main SPEEDY references:

Molteni, F. , 2003, Atmospheric simulations using a GCM with simplified physical parametrizations. I: model climatology and variability in multi-decadal experiments, *Climate Dynamics*, 20, pp. 175-191.

Kucharski, F., F. Molteni, A. Bracco, 2006, Decadal interactions between western tropical Pacific and the North Atlantic Oscillation, *Clim. Dyn.*, 26, pp. 79-91.

Kucharski, F., F. Molteni, M. P. Kin, R. Farneti, I.-S. Kang, L. Feudale, 2013, On the need of intermediate complexity general circulation models: a 'SPEEDY' example. *BAMS* 94: 25-30, DOI: 10.1175/BAMS-D-11-00238.1, <http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-11-00238.1>

Supplementary materials including descriptions for parameterizations, further details of validations, and a list of research papers:

<http://users.ictp.it/~kucharsk/speedy-net.html>

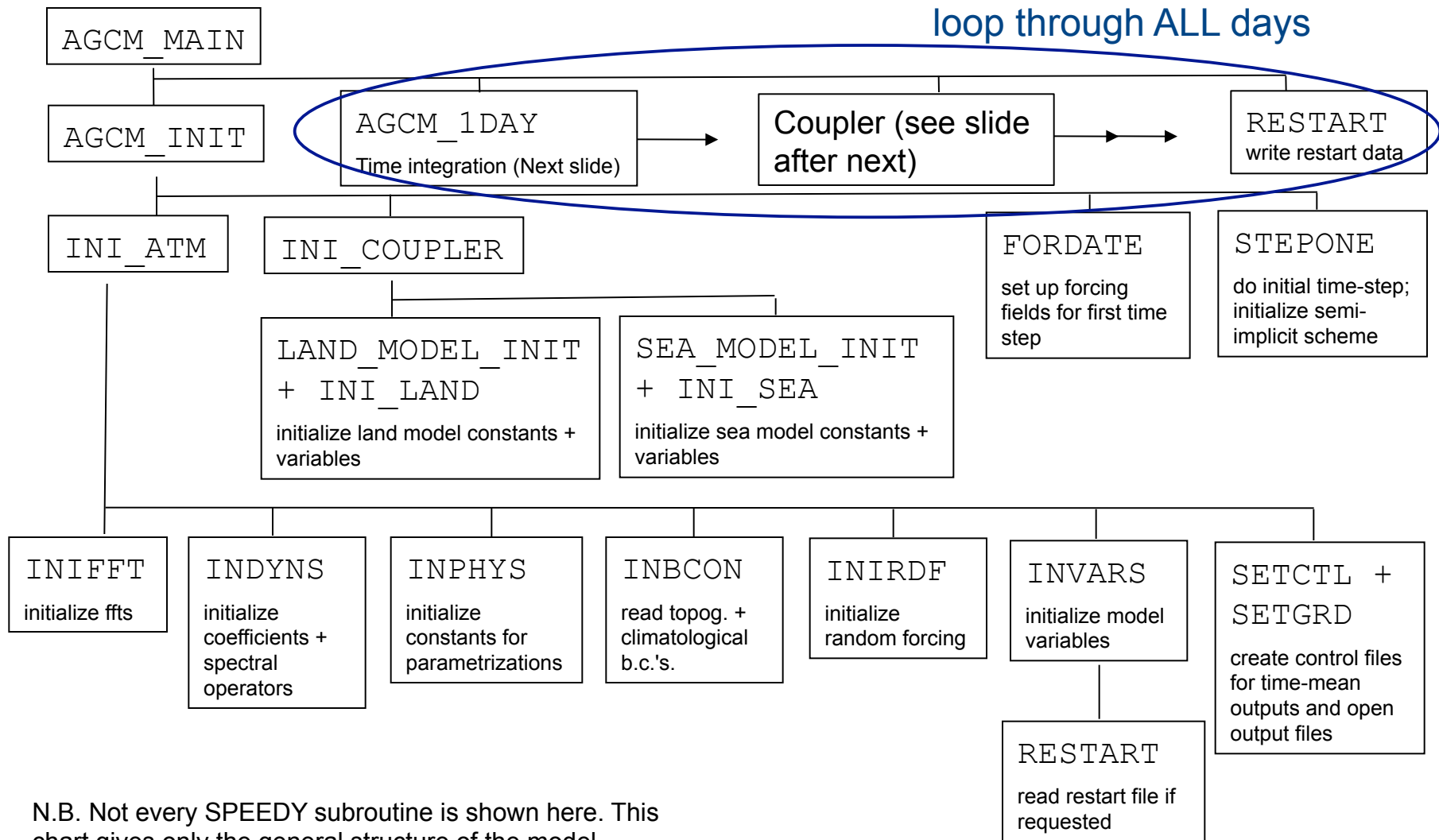
SPEEDY Manual: available in installation pack.

Further arguments for the use of intermediate complexity climate models:

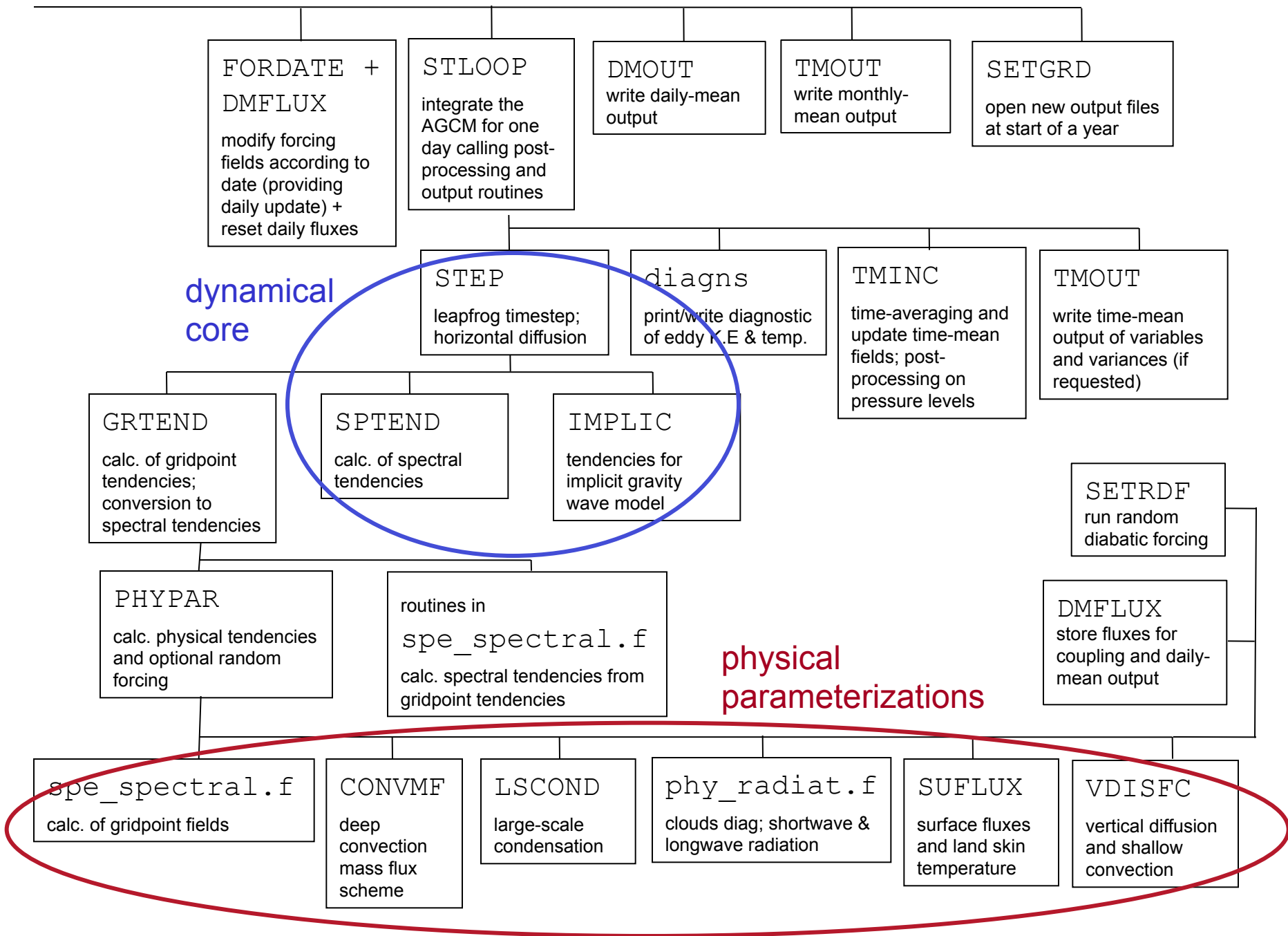
In an opinion article, Isaac Held (Held, The gap between simulation and understanding in climate modeling, BAMS, Nov 2005) argues:

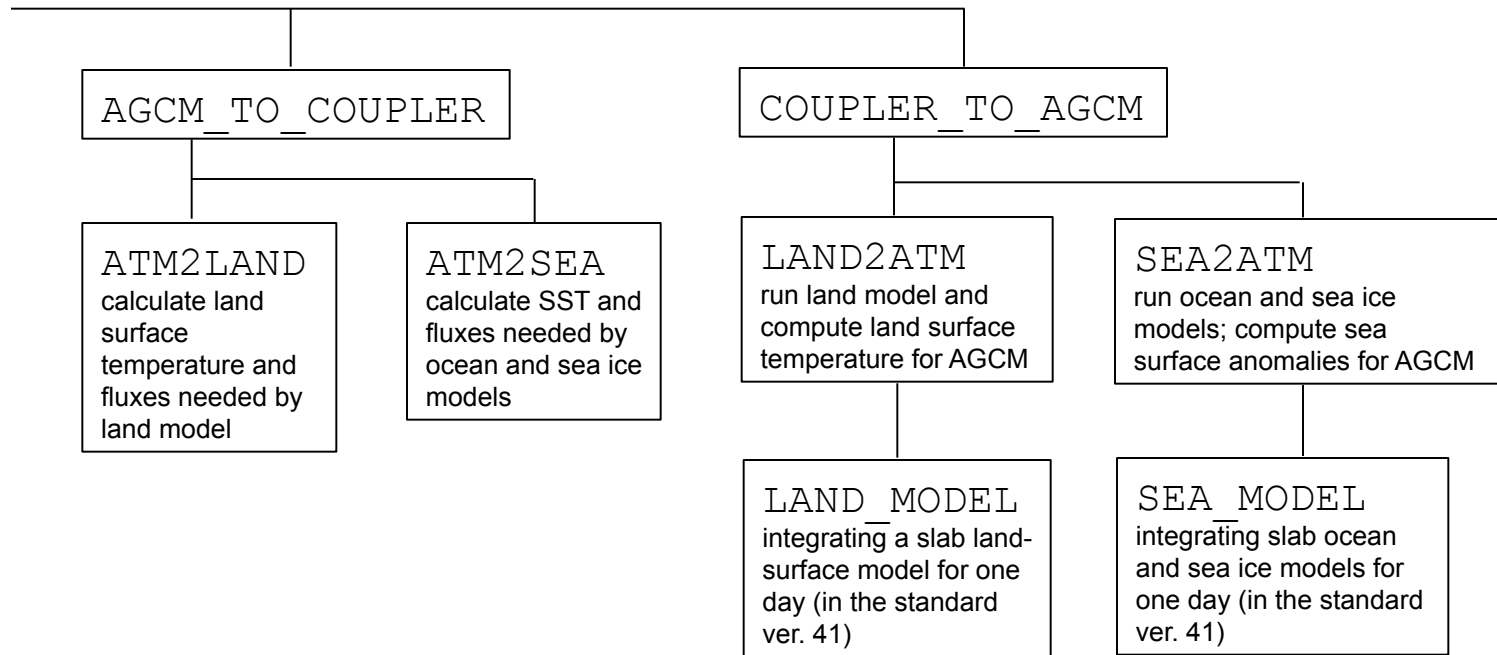
1. “..., we try to simulate by capturing as much of the dynamics as we can in comprehensive numerical models. On the other hand, we try to *understand* by simplifying and capturing the essence of a phenomenon in idealized models, ...”
2. “The health of climate theory/modeling in the coming decades is threatened by a growing gap between high-end simulations and idealized theoretical work. In order to fill this gap, research with a hierarchy of models is needed.”
3. “..., the construction of such hierarchies must, I believe, be a central goal of climate theory in the twenty-first century. There are no alternatives if we want to understand the climate system and our comprehensive models. Our understanding will be embedded within these hierarchies.”

The anatomy of SPEEDY:



N.B. Not every SPEEDY subroutine is shown here. This chart gives only the general structure of the model.





The physiology of SPEEDY:

1. Dynamical core—equations of motion in spectral form

Streamfunction

$$\psi = a^2 \sum_{m=-J}^{+J} \sum_{l=|m|}^{|m|+J} \psi_l^m Y_l^m$$

Velocity potential

$$\chi = a^2 \sum_{m=-J}^{+J} \sum_{l=|m|}^{|m|+J} \chi_l^m Y_l^m$$

Temperature

$$T = a^2 \sum_{m=-J}^{+J} \sum_{l=|m|}^{|m|+J} T_l^m Y_l^m$$

ln(p_{surf})

$$q = a^2 \sum_{m=-J}^{+J} \sum_{l=|m|}^{|m|+J} q_l^m Y_l^m$$

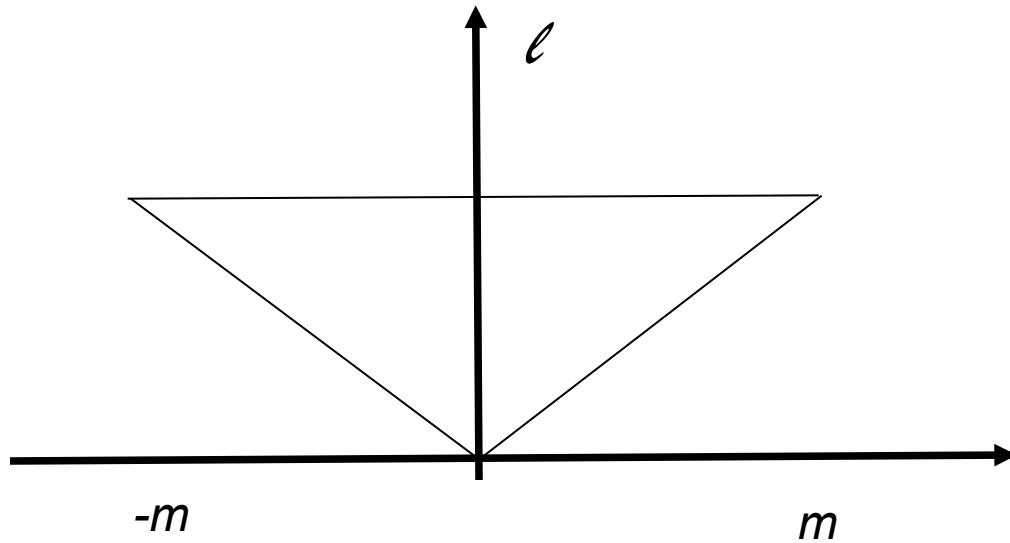
where $Y_l^m = P_l^m(\sin \phi) e^{im\lambda}$.

The prognostic variables, are vorticity $\xi = \nabla^2 \psi$, divergence $D = \nabla^2 \chi$,

Temperature T and logarithm of surface pressure, ln(surface pressure).

N.B. For simplicity of presentation here, I will only use q to illustrate the method, to read more details including meanings of symbols, see Bourke, 1974, A multi-level spectral model I. formulation and hemispheric integrations, Monthly Weather Review, 102, pp.687-701.

Spectral Triangular Truncation



$l - m$ nodal zeros
 m wave numbers

$$\psi = \sum_{m=-J}^J \sum_{l=|m|}^J \psi_l^m Y_l^m$$

where

$$Y_l^m = P_l^m \sin(\varphi) e^{im\lambda}$$

Associated Legendre Polynomial

Spectral tendencies for the *expansion coefficients* can be derived.

related to vorticity, see Eq.(28) in Bourke, 1974.

$$-l(l+1) \frac{\partial \psi_l^m}{\partial t} = \dots$$

related to divergence, see Eq.(29) in Bourke, 1974.

$$-l(l+1) \frac{\partial \chi_l^m}{\partial t} = \dots$$

related to temperature, see Eq.(30) in Bourke, 1974.

$$\frac{\partial T_l^m}{\partial t} = \dots$$

related to surface pressure, Eq.(31) in Bourke 1974, displayed in full here.

$$\frac{\partial q_l^m}{\partial t} = z_l^m - l(l+1) \overline{\chi_l^m} \quad \text{where} \quad \overline{(\quad)} = \int_{\sigma=1}^0 (\quad) d\sigma$$

The coefficient z_l^m arises from a nonlinear term in the original equation for q

$$\bar{V} \cdot \nabla q = \sum_{m=-J}^{+J} z_m e^{im\lambda},$$

which is evaluated in grid-point space and FFT at each latitude circle to spectral space (obtaining z_m). And calculating

$$z_l^m = \int_{-\pi/2}^{\pi/2} z_m P_l^m(\sin \phi) \cos \phi d\phi.$$

The timestepping is evaluated using the leap-frog and semi-implicit schemes:

$$q^{\tau+1} = q^{\tau-1} + 2\Delta t z + \Delta t \left(\bar{D}^{\tau+1} + \bar{D}^{\tau-1} \right)$$

(the sub- and superscript m and l is implied). The solution for $\bar{D}^{\tau+1}$ is obtained by Gaussian elimination (see Sect. 4 of Bourke, 1974).

N.B. See Bourke, 1974 (ref. above) and Sect. 4.5 and Appendix B of Washington and Parker, 2005, An Introduction to Three-Dimensional Climate Modeling, 2nd Ed, University Science Books.

Continuing... the physiology of SPEEDY:

2. Physical parameterizations.

Parameterizations are computed in grid-point space. To have an idea of how a parameterization work, here only the convection scheme is described in detail. For details of other schemes look at Appendix to ver. 41 available on the SPEEDY webpage.

From the primitive variables, U , V , T , Q , Φ and p_{surf} additional diagnostics variables are calculated:

saturation specific humidity: Q^{sat}

relative humidity: RH

dry static energy: $SE = c_p T + \Phi$

moist static energy: $MSE = SE + L_c Q$

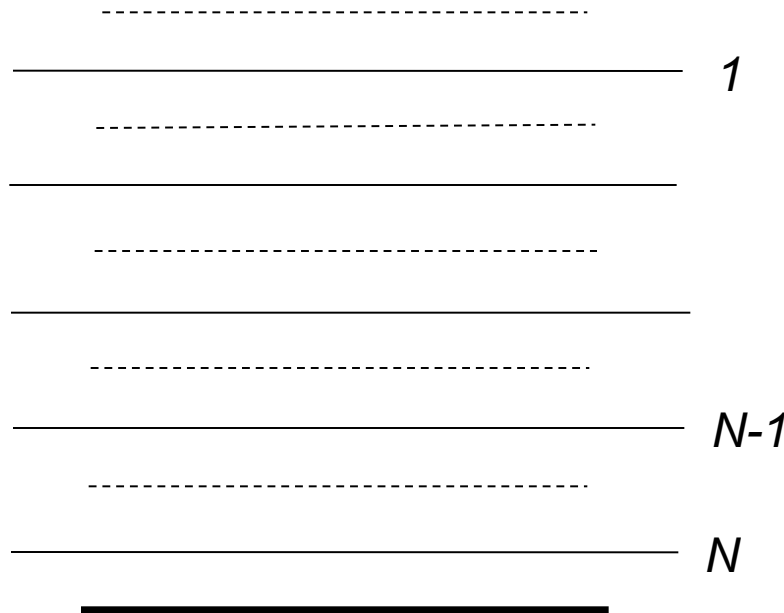
saturation moist static energy: $MSS = SE + L_c Q^{\text{sat}}$

a. Convection

An updraft of saturated and unstable air from the PBL to a top-of-convection (TCN) level in middle or top of troposphere.

Compensating large-scale descending motion.

Entrainment into updraft occurs in lower troposphere above PBL. Detrainment only in TCN level.

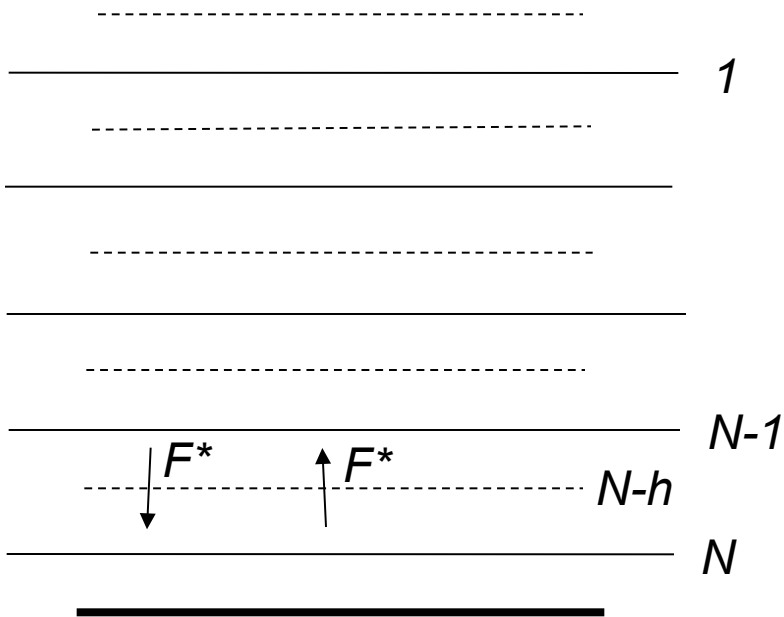


Conditions for activation:

$$Q_N > Q_{thr} = \min(Q_{cnv}, RH_{cnv}, Q_{cnv}^{sat})$$

and, for $1 < k < N-1$,

$$MSS_N > MSS_{k+h}$$



$${}^u F_{N-h}^m = {}^d F_{N-h}^m = F^*$$

$${}^u F_{N-h}^Q = F^* \cdot Q_N^{\text{sat}} \quad {}^d F_{N-h}^Q = F^* \cdot Q_{N-h}$$

$${}^u F_{N-h}^{SE} = F^* \cdot SE_N \quad {}^d F_{N-h}^{SE} = F^* \cdot SE_{N-h}$$

To find F^* , we use

$$\left(\frac{\partial Q_N}{\partial t} \right)_{\text{cnv}} = - \frac{g F^* (Q_N^{\text{sat}} - Q_{N-h})}{\Delta p_N} = - \frac{Q_N - Q_{\text{thr}}}{\tau_{\text{cnv}}}$$

Now we have the necessary fluxes at N-h...
 An entrainment flux is calculated

$$E_{N-1}^m = \varepsilon(\sigma_{N-1})F_{N-h}^m$$

Then fluxes at k-h are calculated:

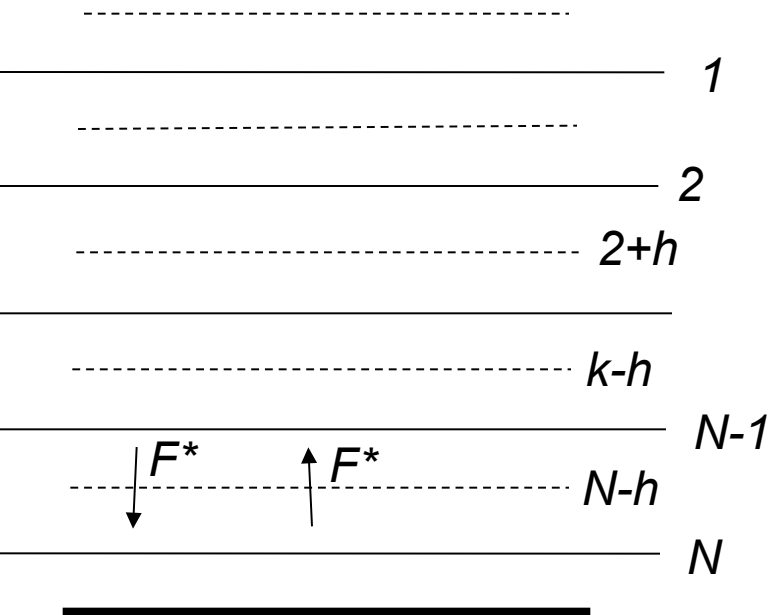
$$F_{k-h}^m = F_{N-h}^m + E_{N-1}^m$$

$${}^u F_{k-h}^Q = {}^u F_{N-h}^Q + E_{N-1}^m Q_{N-1}$$

$${}^d F_{k-h}^Q = F_{k-h}^m Q_{k-h}$$

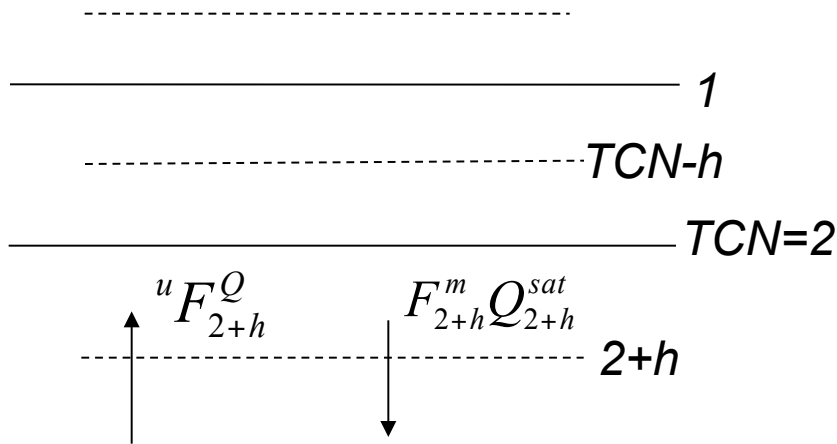
$${}^u F_{k-h}^{SE} = {}^u F_{N-h}^{SE} + E_{N-1}^m SE_{N-1}$$

$${}^d F_{k-h}^{SE} = F_{k-h}^m SE_{k-h}$$



And hence going up all the half-levels until, and including, TCN-h (for the diagram here TCN=2).

Since no detrainment is specified in the 'intermediate' layers, condensation is only computed in the TCN layer. The convective precipitation is the difference between the upward moisture flux and the downward saturated moisture flux:



$$P_{cnv} = u F_{2+h}^Q - F_{2+h}^m Q_{2+h}^{sat}$$

N.B. no fluxes are specified across TCN-h

The net fluxes of moisture and energy into the TCN layer are modified as:

$$\Delta F_2^Q = u F_{2+h}^Q - d F_{2+h}^Q - P_{cnv}$$

$$\Delta F_2^{SE} = u F_{2+h}^{SE} - d F_{2+h}^{SE} - L_c P_{cnv}$$

A net flux is converted into tendency of the respective variable according to the method described in of sect. A.1 of Appendix to Molteni, 2003. The net fluxes and thus tendencies for moisture and dry static energy can be computed.

b. Other schemes (no less important but I don't have time to describe them in details here):

Large-scale condensation: Where relative humidity exceeds height-dependent thresholds, specific humidity is relaxed (represents 'raining') to the corresponding threshold on a 4hr timescale. The released latent heat is converted to dry static energy.

Clouds: Cloud cover and thickness are diagnosed from relative and absolute humidity.

Shortwave radiation: Two spectral bands. Reflected at cloud top and 'earth' surface. Cloud albedo is related to cloud cover. SW transmissivities of model layers are functions of layer thickness, specific humidity.

Longwave radiation: Four spectral bands. One for atmospheric infrared window, one for CO₂ and two for water vapour.

Surface fluxes of momentum and energy: Defined by bulk aerodynamic formulas with different exchange coefficients from land and sea.

Vertical diffusion: Redistribution of dry static energy and moisture between two lowest layers in conditional instability. Water vapour diffusion. Diffusion of dry static energy if lapse rate exceeds the dry adiabatic limit.

A summary of SPEEDY features

Spectral dynamical core

Truncation at T30 (~3.75x3.75 degrees)

8 vertical levels

Variables: Vor, Div, T, $\log(p_{\text{surf}})$ and Q

Physical parameterizations of

- Convection (mass flux)

- Large-scale condensation (RH criterion)

- Clouds (diagnosed)

- Short-wave radiation (two spectral bands)

- Long-wave radiation (four spectral bands)

- Surface fluxes of momentum and energy (bulk formulas)

- Vertical diffusion

Land-temperature calculated in simple model of 1-m soil layer

Slab ocean option

New feature of version 41.5: Daily cycle of solar radiation

Fields of model climatology

(see <http://users.ictp.it/~kucharsk/speedy-net.html>)

Suggested further readings:

Washington and Parkinson, 2005, **An Introduction to Three-Dimensional Climate Modeling**, 2nd Ed, University Science Books.

Journal of Climate, Volume 19, Issue 11 (June 2006), A special issue on CCSM3.