Parameterization of atmospheric turbulence

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Entrenamiento en Modelado Numérico de Escenarios de Cambio Climático

Cachoeira Paulista SP, 30 agosto – 4 de septiembre de 2009

Main sources:

Mesinger, F., 199x: Boundary layer, turbulence transports, horizontal diffusion. Abdus Salam International Centre for Theoretical Physics (ICTP), Lecture notes, 199x, 23 pp (pdf available at …)

Mesinger, F., 2000: Several Eta model PBL lessons: Turbulence closure surface fluxes, molecular sublayer, Mellor-Yamada 2.5 length scale, and realizability problem. Unpublished manuscript.

Mesinger, F., S. C. Chou, J. L. Gomes, D. Jovic, . . . , 2009: An upgraded version of the Eta model. Manuscript in preparation.

Contents: (of the PBL lecture notes, more relevant items listed below !)

- Turbulence? Turbulence transports/methods used;
- Turbulence closure. Example: Mellor-Yamada (MY) 2.5;
- Realizability and master length scale issues of the MY 2.5;
- The surface layer: Monin-Obukhov (MO) similarity;
- MO issues: free convection/the Beljaars correction, the Zilitinkevich extension for the stable case, BL "structures”;
- The molecular sublayer;
- Horizontal diffusion: do we need it, if so why/ what is it?

Turbulence?

Exists (an observed fact!)

Results in important transports

Transports:

- *Advection*/ transports by model-resolved motions;
- *Turbulence* transports: transports by turbulence eddies;
- Near the ground surface: *molecular* transports

1. Turbulence transports/ methods used:

Horizontal turbulence transports are unimportant/negligible with resolved horizontal scales much larger than the vertical scale - as is the case in regional atmospheric models (e.g., Mellor 1985). Or, Bougeault (1997, p 79): three-dimensional turbulence effects "become important only when the horizontal resolution approaches 1 km".

Thus: *vertical* transports. The typical approach: for a specific variable A (quantity per unit volume: ρA), define "exchange coefficient" K_A by

$$\frac{\partial A}{\partial t} = \frac{\partial}{\partial z}\left(K_A \frac{\partial A}{\partial z}\right) \qquad (1)$$

Fundamental task: determine K_A.

Very large variety of schemes. Some recent references: Bougeault (1997); reports which follow Nielsen (1999).

- Schemes expressing K_A as a function of model-resolved variables (shear, buoyancy / Richardson number, ...) Examples: "Louis" scheme, "Holtslag" scheme, ... (e.g., Louis 1979, Rummukainen 1999, ...)

- Schemes with a prognostic equation for the turbulence kinetic energy (TKE). Popular member: Mellor-Yamada level 2.5

- Schemes with two and more prognostic equations for turbulence quantities. E.g., TKE-e schemes, Mellor-Yamada level 3 or more, ...

Also: non-local schemes, not following (1), or not only following (1).

Turbulence closure:

- Consider variables consisting of mean values, and fluctuations,

  e.g.: $$\tilde{u} = U + u, \quad \tilde{v} = V + v, \quad ..., \tag{2}$$

- Assume a set of properties for ensemble averaging ("Reynolds averaging"):

  $$\overline{AB} = AB + \overline{ab} \qquad \bar{\bar{A}} = \bar{A} \quad \cdots \tag{3}$$

- Assume that the mean values satisfy the governing equations; write them ---> (4)

- Write governing equations for the total values: ---> (5)

- Subtract (4) from (5), to obtain prognostic equations for u, v, ... (In tensor notation: u_j, and θ) ---> (6).

New variables appear as a result of (3):

$$\overline{u_i u_j} \qquad \overline{u_j \theta} \tag{7}$$

"Reynolds stresses". These are the variables we need to describe the effect of turbulence on mean quantities. However, more variables than prognostic equations: *the closure problem*.

Get prognostic equations for Reynolds stresses by time differentiating (7) and inserting from (6).

However, yet additional new variables:

$$\overline{u_k u_i u_j} \qquad \overline{p u_j} \qquad \overline{u_i u_j \theta} \qquad \overline{p \theta}$$

A variety of assumptions by numerous people.

Mellor and Yamada (1974, 1982):

Assumptions due to Kolmogorov, 1942, and Rotta, 1951. Tensor symmetry properties, dimensional analysis considerations. Analyze terms with respect to order of deviation from isotropy. Introduce systematic simplifications based on the assumption that the degree of anisotropy is small.

---> terms including a variety (five) of length scales

Assumption: all five length scales proportional to a single *"master length scale"*, l

Mellor-Yamada "level 2.5": reduce the problem to just one prognostic equation ("M-Y 2.5"); very popular – many models

$$\frac{d(q^2/2)}{dt} - \frac{\partial}{\partial z}\left(lqS_q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right) = P_s + P_b - \varepsilon\ ,$$

where

$$q^2 = u^2 + v^2 + w^2\ ,$$

is twice the turbulence kinetic energy. P_s and P_b: shear and buoyancy production, given by

$$P_s = -\overline{wu}\frac{\partial U}{\partial z} - \overline{wv}\frac{\partial V}{\partial z}\ ,$$

$$P_b = \beta g \overline{w\theta_v}\ ;$$

Dissipation, ε, is given by

$$\varepsilon = \frac{q^3}{B_1 l}.$$

S_q, β, and B_1 above are constants. Exchange coefficients for momentum and heat, K_M and K_H, are

$$K_M = lqS_M, \quad K_H = lqS_H.$$

The "stability functions" S_M and S_H can be calculated from

$$G_M = \frac{l^2}{q^2}\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right],$$

$$G_H = -\frac{l^2}{q^2}\beta g \frac{\partial \Theta_V}{\partial z},$$

via equations that involve additional constants (Mellor and Yamada 1974, 1982; also Janjic 1990).

The realizability problem: solving for S_M and S_H -- ill-conditioned in a region of the G_M, G_H plane. Janjic (1990, similar to MY 1982):

$$G_H \le 0.024, \quad G_M \le 0.036 - 15\,G_H\,.$$

Struggling: Helfand and Labraga (JAS, 1988); Galperin et al. (JAS 1988: level 2 1/4 scheme).

In the Eta: rather than restrict G_H, G_M, restrict l

Mesinger (1993a), Janjic (1996)

4. The surface layer: Monin-Obukhov similarity

"Surface layer": shallow layer where *the turbulent fluxes differ little form their surface value.* Extending from the ground to some meters above. ("Some meters": 5 to 50 m)

Also "constant flux layer". Warning: this is precisely the layer in which the turbulent fluxes change most rapidly!

"Atmospheric surface layer", ASL

Basic notation. Consider the "neutral" case first: heat transport not having a significant impact. (Always near the surface).

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Relevant variables: height, z, and "friction velocity", u_*, defined by

$$u_* u_* = -\overline{u'w'}\ .$$

Also: "velocity scale".

Momentum profile:

$$\frac{du}{u_*} = \frac{dz}{l}$$

where

$$l = kz$$

is a characteristic length scale, or eddy size. k: von Karman constant, 0.4. For traditional reasons, we have here changed notation to use lower case u for the mean velocity. Integration leads to

$$u = \frac{u_*}{k} \ln \frac{z}{z_0}\ . \qquad (8)$$

"The logarithmic wind profile". z_0: "roughness length". However: "roughness length for momentum", z_{0u}, better.

Stratification (Monin-Obukhov):

Sensible heat flux, $-\overline{w'\theta'}$, is relevant. Traditional: define "temperature scale", θ_*, by

$$\theta_* u_* = -\overline{\theta' w'}\ .$$

Using this temperature scale (in fact, sensible heat flux), "Monin-Obukhov" (MO) length is defined, e.g., by

$$L = \frac{u_*^{\,2}\Theta}{kg\theta_*}\ . \qquad (9)$$

Nondimensional height can now be formed, z/L, and instead of the $\frac{du}{dz}=\frac{u_*}{kz}$, etc., MO similarity states that

$$\frac{du}{dz}=\frac{u_*}{kz}\Phi_u(\frac{z}{L}), \qquad \frac{d\Theta}{dz}=\frac{\theta_*}{kz}\Phi_\theta(\frac{z}{L}), \tag{10}$$

etc. Φ_u, Φ_θ, .., : functions obtained from measurements. "Empirical functions".

To compute fluxes, we need the exchange coefficients K_M and K_H, defined by

$$-\overline{u'w'}=K_M\frac{du}{dz}, \qquad -\overline{\theta'w'}=K_H\frac{d\Theta}{dz} \tag{11}$$

Solving (10) not straightforward. Highly implicit. Note: L is a function of the momentum and sensible heat flux, given by K_M and K_H, which we want to obtain. However: standard methods. Two elevations needed;

What about very close to the ground?

Molecular transports take over !!

In the Eta:

Different over land (and ice) and over water

Over land (and ice):
Account for roughness elements:

Zilitinkevich (1995)

$$z_{0T} = z_{0m} e^{-A_0 \sqrt{u_* z_{0m} / \nu}}$$

Over water:
Molecular sublayer

Liu, Katsaros, Businger (1979, "LKB");
Janjic (1994);
also: "An upgraded version of the Eta model"

Molecular sublayer:

according to measurements of Mangarella et al. (1973):

Three regimes: smooth, rough, and rough with spray;

The flow switches from one to the other according to the value of “roughness Reynolds number”, Rr

$$Rr = u_* z_0 / \nu$$

Seems to work well, an example:

Typhoon Yancy (Aug. 1990)

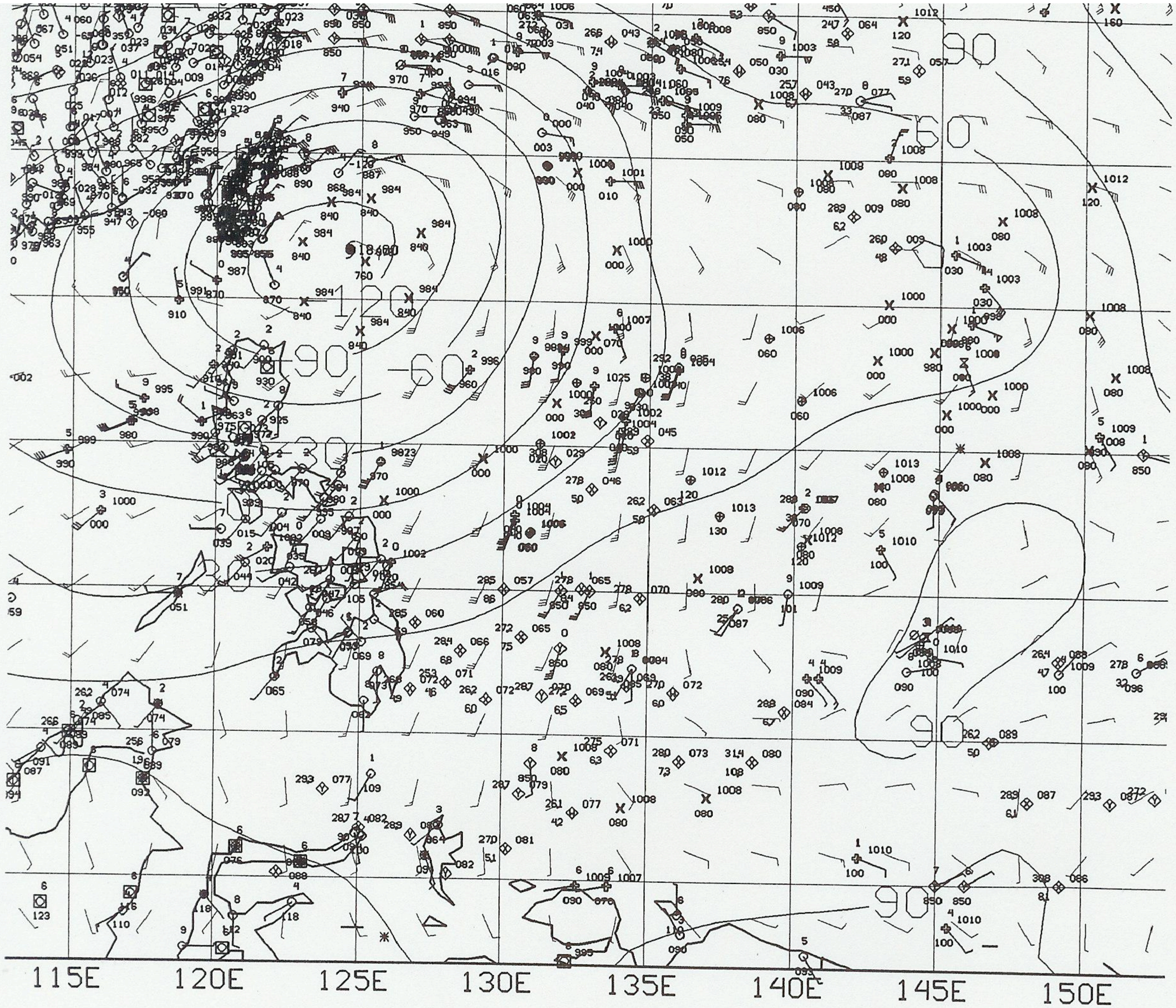


Figure 3. A section of the NMC TCM-90 surface analysis valid 0000 UTC 18 August 1990 (Courtesy of Eric Rogers). Contours of analyzed 1000 mb geopotential heights, in meters, and winds, in knots, are shown; as well as various observations.

Without molecular sublayer:

With molecular sublayer:

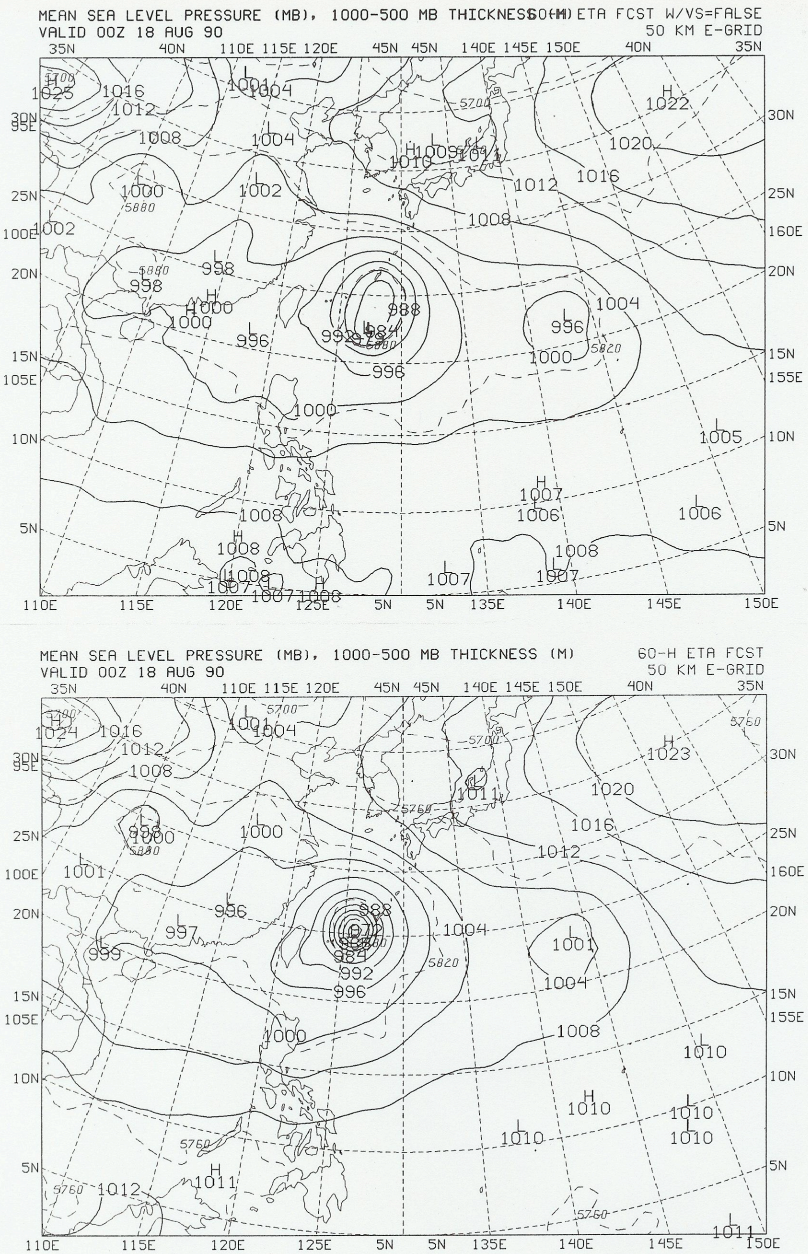


Figure 4. The Eta Model 60-h simulation of the sea level pressure, millibars, and 1000-500 mb thickness, meters, valid 0000 UTC 18 August 1990, with no parameterization of the molecular sublayer, upper panel; same except for the parameterization of the molecular sublayer being included, lower panel. (Courtesy of Eric Rogers.)

"What have you done for me lately?"

$$\nu \frac{U_1 - U_s}{z_{1u}} = u_* u_*,$$

$$\kappa \frac{\Theta_1 - \Theta_s}{z_{1\theta}} = \theta_* u_*, \tag{8.1}$$

$$\varepsilon \frac{q_1 - q_s}{z_{1q}} = q_* u_*,$$

where ν, κ, and ε are the kinematic viscosity, thermal diffusivity, and molecular diffusivity of water vapor, respectively; u_* is the friction velocity, and θ_* and q_* are analogously defined scaling parameters for the sensible heat and moisture fluxes, respectively. The right hand sides of (8.1) can also be expressed in terms of the standard surface layer bulk relationships, and the equations thus obtained solved for U_1, Θ_1 and q_1 provided sublayer thicknesses are known. These were obtained by Janjic by postulating

$$\frac{z_{1u} u_*}{C\nu} = \frac{z_{1\theta} u_*}{S\kappa} = \frac{z_{1q} u_*}{D\varepsilon} = \zeta, \tag{8.2}$$

It was considered by Janjic adequate to keep ζ a constant. For $Rr \approx 1$ one obtains

$$\zeta = 0.35 \tag{29}$$

Used in the "standard" Eta

As opposed to having ζ constant, a relationship resulting from experimental data (Brutsaert 1982, Fig. 4.1) can be used:

A question can be asked: if the linear profile at the bottom of the viscous sublayer is linearly extrapolated upwards, and the logarithmic profile of the surface layer is at the same time logarithmically extrapolated downwards, at what elevation will the two extrapolated profiles intersect? This should be the appropriate value of z_{1u}, from which ζ can be calculated.

One obtains

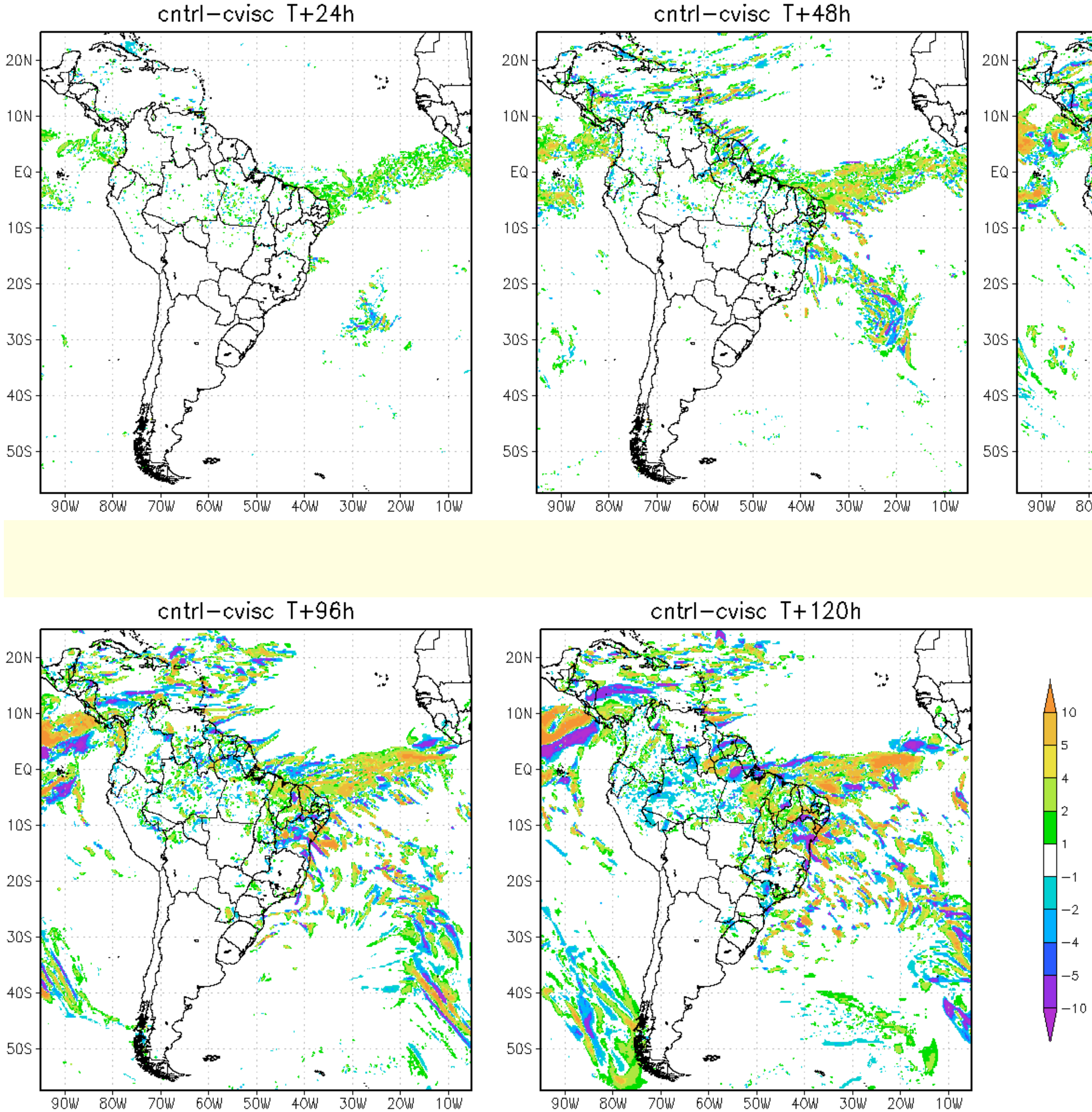
$$\zeta = 11 / (M\,Rr^{1/4})$$

The model knows what is *Rr* :

Relation originally due to Charnock widely used; in the Eta:

$$z_0 = \frac{0.11\nu}{u_*} + \frac{0.018 u_*^2}{g}$$

0.018: *the Charnock constant*; for further reading see e.g., Garratt (1992, pp. 98-100).



Difference, accumulated precip, mm/24 h, initial condition 27 Apr 2009

Some of the references (if missing, check the lecture notes cited on slide 2):

Bougeault, P., 1997: Physical parametrizations for limited area models: Some current problems and issues. *Meteor. Atmos. Phys.*, 63, 71-88.

Brutsaert, W., 1982: *Evaporation into the Atmosphere*. Reidel, Dordrecht, 299 pp.

Janjic, Z. I., 1990: The step-mountain coordinate: physical package. *Mon. Wea. Rev.*, **118**, 1429-1443.

Janjic, Z. I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927-945.

Janjic, Z. I., 1996a: The Mellor-Yamada level 2.5 scheme in the NCEP Eta Model. *11th Conf. on Numerical Weather Prediction*, Norfolk, VA, Amer. Meteor. Soc., 333-334.

Liu, W. T., K. B. Katsaros, and J. B. Businger, 1979: Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.*, **36**, 1722-1735.

Mangarella, P. A., Chambers, A. J., Street, R. L., and Hsu, E. Y.: 1973: Laboratory studies of evaporation and energy transfer through a wavy air-water interface', *J. Phys. Oceanogr.*, **3**, 93-101.

Mellor, G. L., 1985: Ensemble average, turbulence closure. *Advances in Geophysics, Issues in Atmos. and Ocean Modeling. Part B: Weather Dynamics*, S. Manabe, Ed. Academic Press, 345-357.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20**, 851-875.

Mesinger, F., 1993a: Forecasting upper tropospheric turbulence within the framework of the Mellor-Yamada 2.5 closure. *Research Activities in Atmospheric and Oceanic Modelling*, WMO, Geneva, CAS/JSC WGNE Rep. No. 18, 4.28-4.29.

Zilitinkevich, S. S., 1995: Non-local turbulent transport: Pollution dispersion aspects of coherent structure of convective flows. Air Pollution III - Volume I: *Air Pollution Theory and Simulation*. H. Power, N. Moussiopoulos and C. A. Brebbia, Eds. Computational Mechanics Publications, Southampton Boston, 53-60.