Integrated modelling systems

(Simplified and generalized view)

Serge Ivanov, OSENU

?

Model Simulation = True Atmospheric State

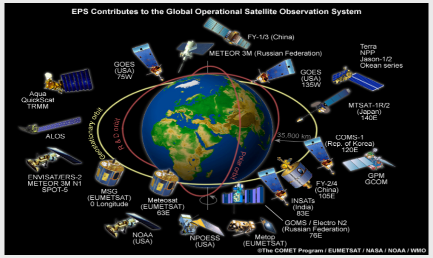
?

Model Simulation = True Atmospheric State

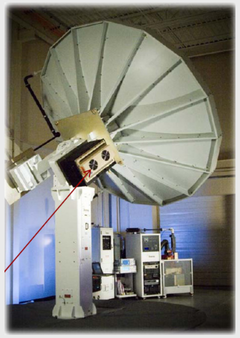
- *Dynamical block*: underestimation of synoptic activity and blocking; polarward shifting of storm-track, …
- *Physical block*: latent heat flux over the ocean; stratiform cloudiness; gravity waves over orography; …

Ingleby, 2001; Jung, 2005; Klinker et al, 1998; Montani et al, 1999; Reynolds et al, 2005; Simmons and Hollingsworth, 2002; Zhou et al, 1996;

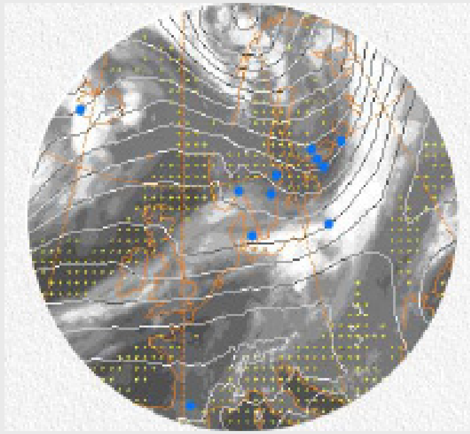
Progress in forecasting



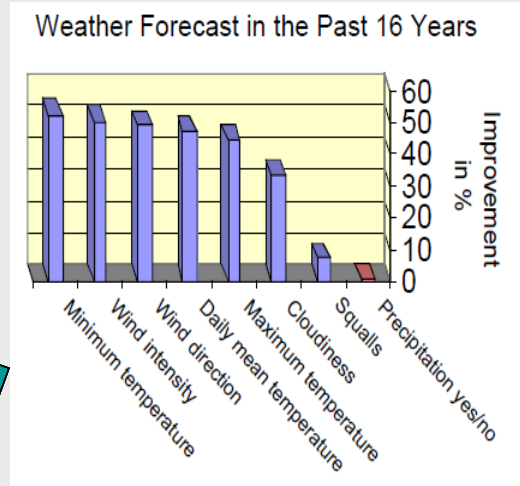
Remote sensing



Computer facilities



<u>Model developments:</u>
Dynamical core,
Physics,
DA
Resolution



Hense et al, 2003

Progress !?

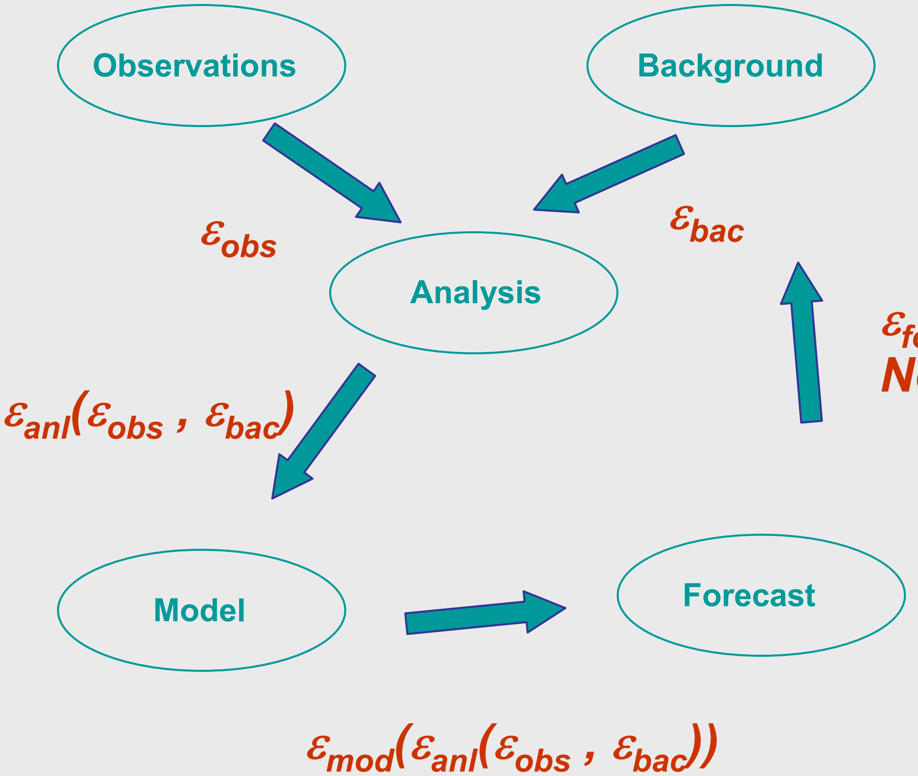
Reasons

- Imperfect knowledge about phys, chem, met processes
- Do you think so or do you know that ?
- Assumptions in meteo description by differential and integral equations
- Geostrophic, hydrostatic, Boussinesq, …
- Approximation of differential equations by finite differences
- $dx/dt \rightarrow$ *lim* $(\Delta x / \Delta t)$, $\Delta t \neq> 0$
- Errors and uncertainties in initial conditions
- Accuracy of observation systems is limited + non-unique transfer functions for remote sensing + representativeness error
- Sensitivity to the above stuff in IC
- Remove the noise and stress the signal, but how do separate them?

Last but not least: Predictability of the atmosphere

? Lyapunov (in-)stability

Error flow



$\varepsilon_{for}(\varepsilon_{mod}, \varepsilon_{anl}, \varepsilon_{obs}, \varepsilon_{bac})$

Non-separable components

Forecast – Truth = Error

! - ? = ?

Direct estimating of the error

<u>is not available</u>

Both the <u>FORECAST</u> and <u>FORECAST ERROR</u> are important

Model stages

- **Observation (gathering, controlling, screening, …)**
- **Data Assimilation –finding a statistically optimal atmospheric state (nudging, OI, nD-var, KF, …)**
- **Model Initialization – creating IC satisfying physical consistency (L(N)NMI, DF, diabatic, …)**
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- **Post-Processing – comfortable issue for users (model levels => mandatory and non-mandatory surfaces, 2m temp, 10m wind, … , visualization, …)**

Model stages

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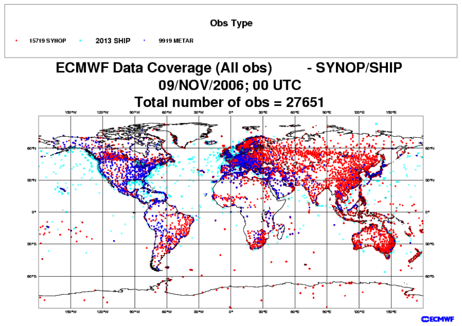
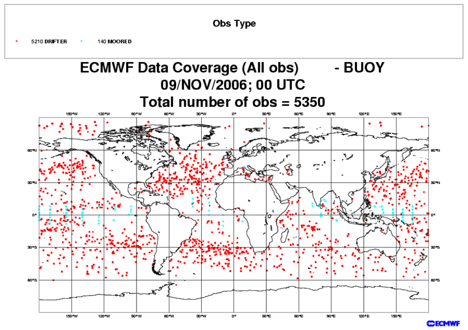
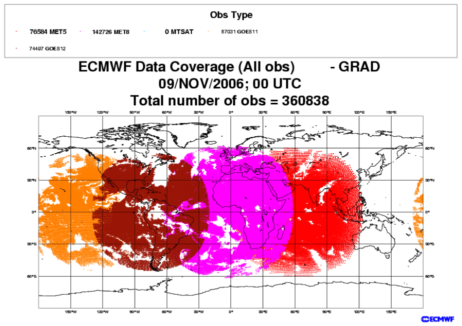
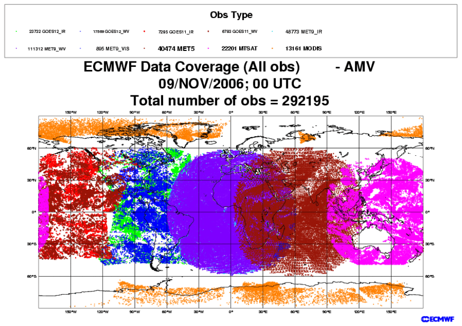
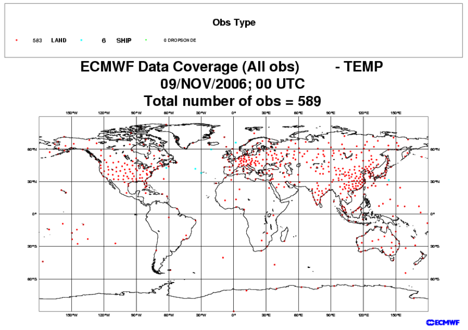
Observation types

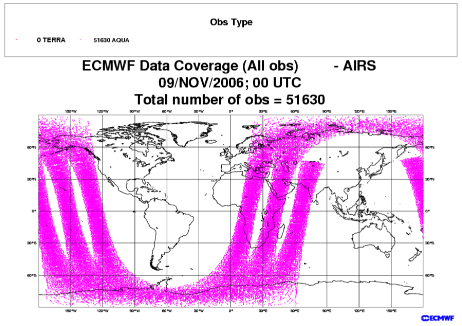


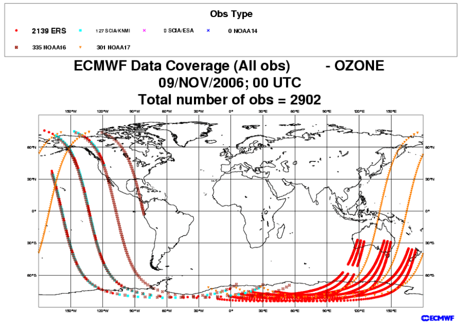


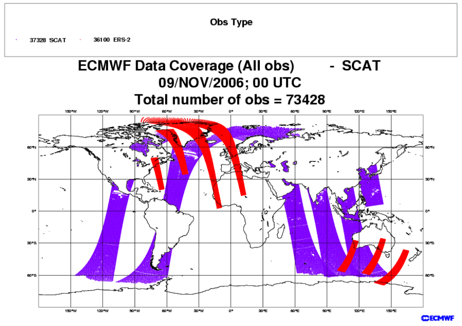


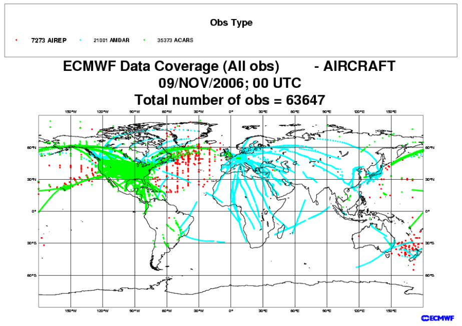


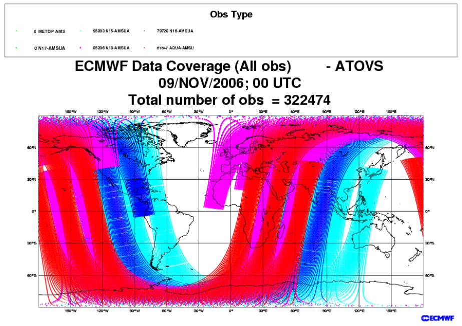


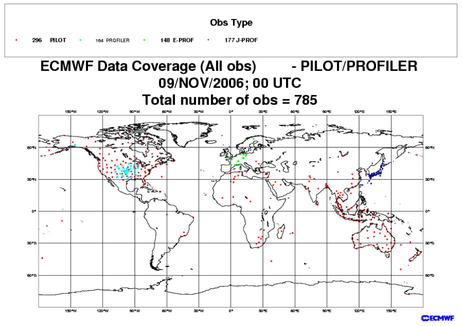


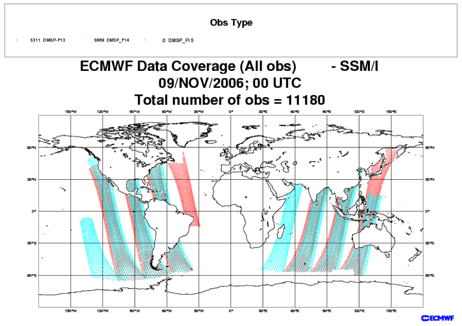












Model stages

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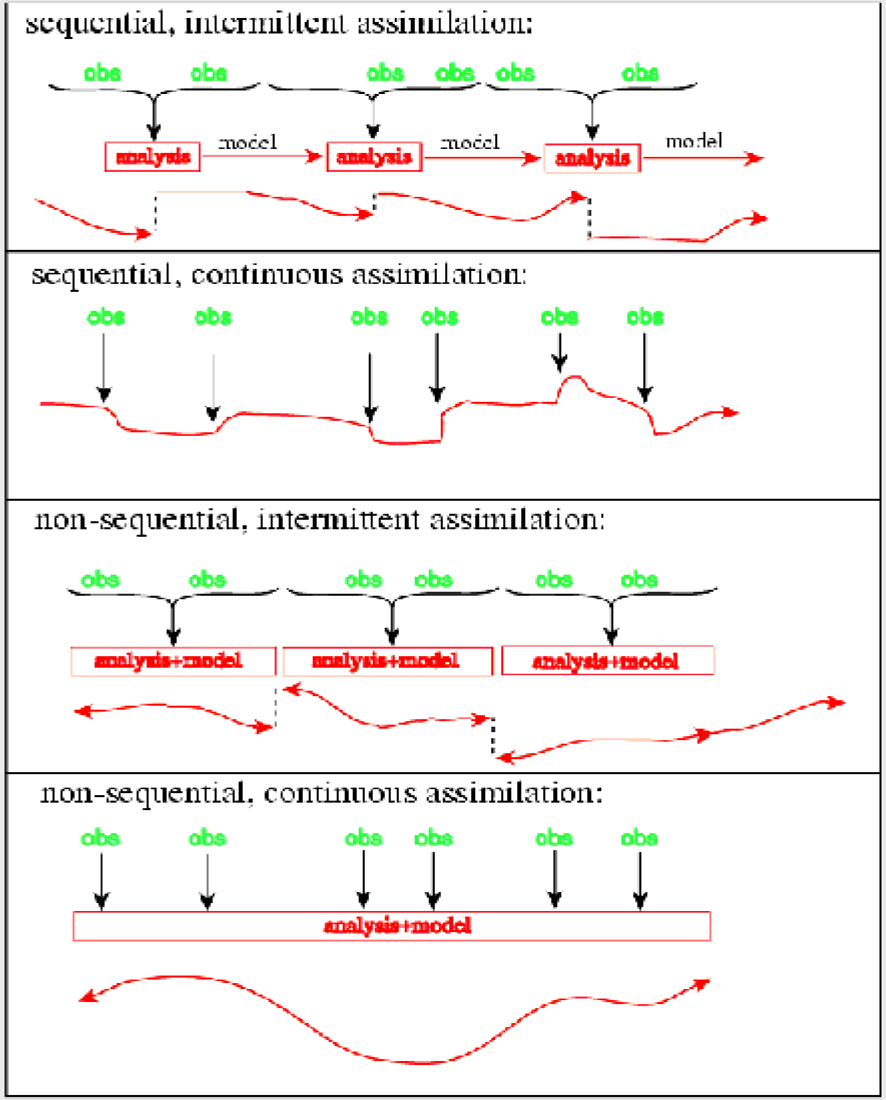
Data assimilation



$$J(\delta x) = J^b(\delta x) + J^o(\delta x)$$

Background Term

Observation Term

(Courtier et al, 1994)

(Holm, 2003, ECMWF)

Model stages

- Observation (gathering, controlling, screening, …)
- Data Assimilation –finding a statistically optimal atmospheric state (nudging, OI, nD-var, KF, …)
- Model Initialization – creating IC satisfying physical consistency (L(N)NMI, DF, diabatic, …) but also allowing perturbations of various nature
- Dynamical Core – numerical solver (Grid, Spectral, FE, Eulier, Lagrange, …)
- Physical Parameterization – taking into account unresolved scales (Microphysics, Convection, PBL, Radiation, Orography Drag, Diffusion, …)
- Post-Processing – comfortable issue for users (model levels => mandatory and non-mandatory surfaces, 2m temp, 10m wind, … , visualization, …)

Model Initialization

$$J(\delta x) = J^b(\delta x) + J^o(\delta x) + J^c(\delta x)$$

Physical consistency in the model (compatibility of the mass, wind, temp, …, fields)
controlling high-frequency modes

Latent Heat Nudging – is a sophisticated scheme used for nowcasting

LNMI, NNMI is good for a global domain, but restricted for a regional domain and meso-scale process initialization

DF is preferable for regional domains. It dumps high-frequency perturbations within a domain as well as on lateral and top boundaries

Model stages

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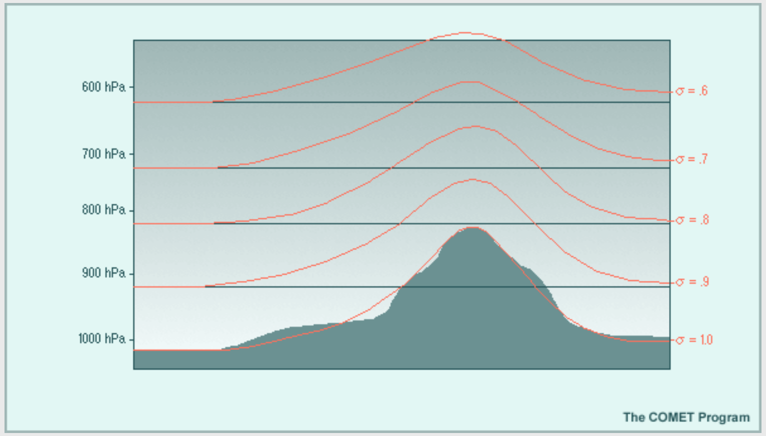
Dynamical Core

See Eigil Kaas' lectures

+

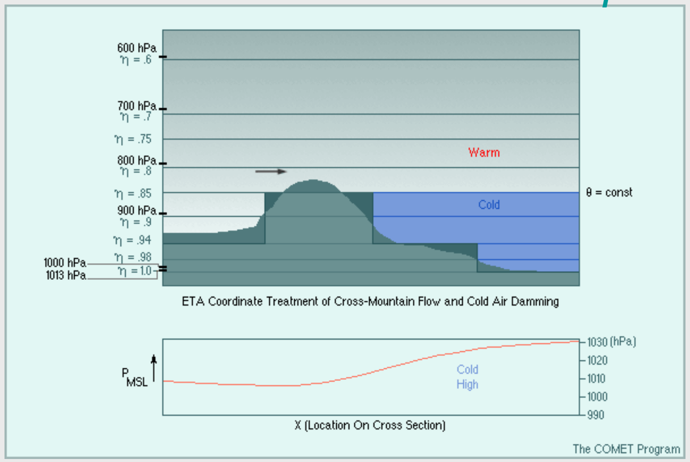
vertical coordinate systems

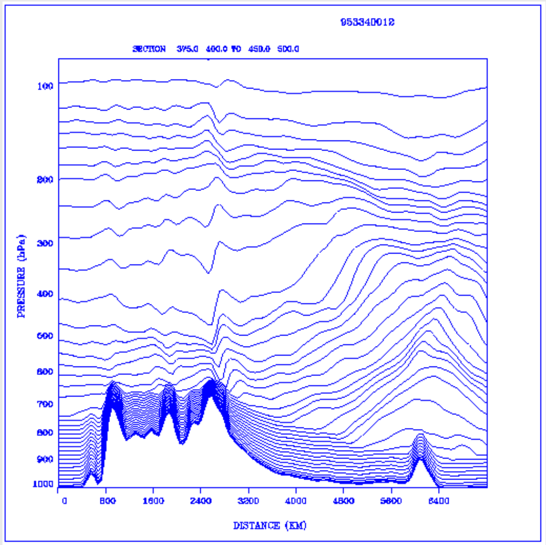
Vertical Coordinate Systems



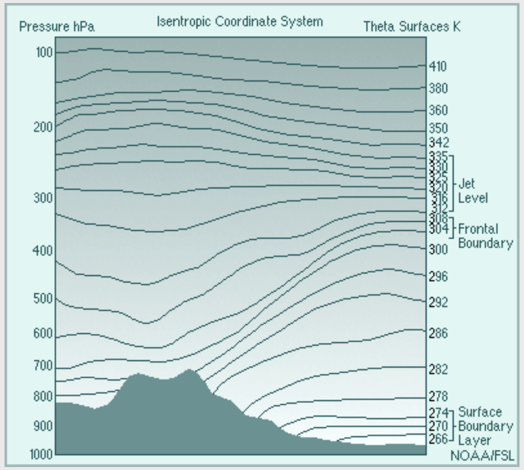
σ-system
terrain-following

Eta-system
step-mountain





Hybrid system



θ-system

http://www.srh.noaa.gov

Vertical Coordinate Systems

System	Advantages	Drawbacks
Sigma (Phillips, 1957)	Accounting terrain Different step in PBL and upper layers No crossing between CS and TS	Different slope values over complex terrain => error in PG, advection, lateral diffusion => noise generation Increased horizontal resolution => Higher slope of CS Requires an additional term to compute PG Difficulties in computations on the lee side of terrain Distorted coastline due to the smooth orography requirement
Eta (Mesinger et al, 1988)	The reference surface is on the sea surface Simple computations and transformation due to the flat basis at every box Realistic simulations over steep orography and on the mountain lee side Better precipitation forecast	Difficulty for detailed description of PBL on a large domain The low slope is approximated by one step Requires to set up interior boundaries on vertical walls Not allowing vectorization Requires equal steps in PBL to ensure equivalence in air-surface interactions Similarity theory does not work when vertical step is larger 100 m Requires the assumption of balance between generation and dissipation of TKE within PBL
Theta (Shapiro and Hastings, 1973)	Potential vortex characteristics are conserved Precipitation spin up is short Increases vertical resolution in strong baroclinic areas Better describes horizontal and vertical wind shear Adiabatic vertical motions are already included in prognostic equations for horizontal wind components	CS and TS can cross CSs vary during a day Vertical step is not monotonic Pure resolution within thick adiabatic layer Does not allow combination with another systems

PBL – planetary boundary layer
PG – pressure gradient
CS – coordinated surface
TS – terrain surface
TKE – turbulent kinetic energy

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PBL parameterization
(numeric problems)

<u>**Level 2.5 closure** (*Mellor and Yamada, 1974*)</u>

Algorithm for generation and dissipation of TKE

$$\frac{\partial q}{\partial t} = Aq^2$$

$$A = \left[S_M G_M + S_H G_H - B^{-1} \right] l^{-1}$$

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

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

S_M, S_H – moment and heat fluxes
U, V – wind components,
q – substance,
l – Monin-Obukhov length,
β, B – empirical constants.

Finite difference approximation

$$q^{\tau+1} = q^{\tau} + A^{\tau} \Delta t \left(q^{\tau+1} \right)^2$$

Two roots

$$q_1^{\tau+1} = \left[1 - \left(1 - 4 A^{\tau} q^{\tau} \Delta t \right)^{1/2} \right] \left(2 A^{\tau} \Delta t \right)^{-1}$$

always > 0 – physical solution

$$q_2^{\tau+1} = \left[1 + \left(1 - 4 A^{\tau} q^{\tau} \Delta t \right)^{1/2} \right] \left(2 A^{\tau} \Delta t \right)^{-1}$$

can be < 0 – numerical solution

PBL parameterization
(numeric problems)

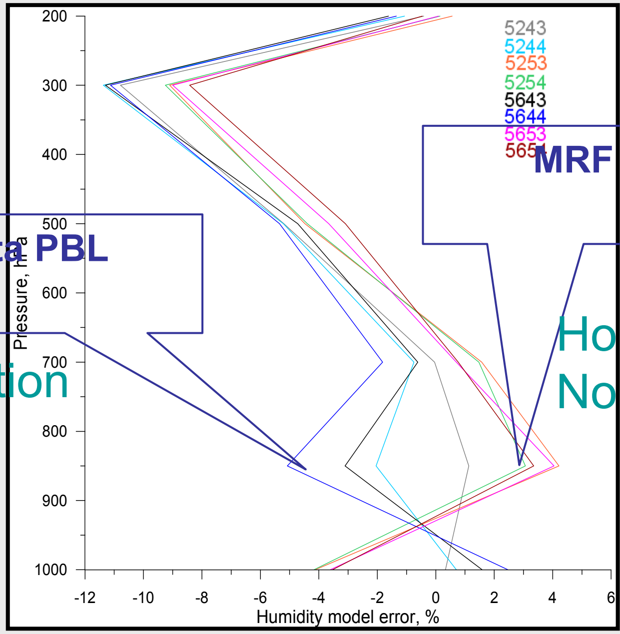
Level 2.5 closure (*Mellor and Yamada, 1974*)

$$Adv\left(v, q^2\right)_{(L+l/2)} = 0{,}5\left[Adv\left(v_L, q^2_{L+l/2}\right) + Adv\left(v_{L+1}, q^2_{L+l/2}\right)\right]$$

- Split numerical scheme can bring **ТКЭ < 0**

* TKE ➔ ∞ => numerical instability => restriction for TKE generation => loosing realistic description

Sensitivity to PBL scheme

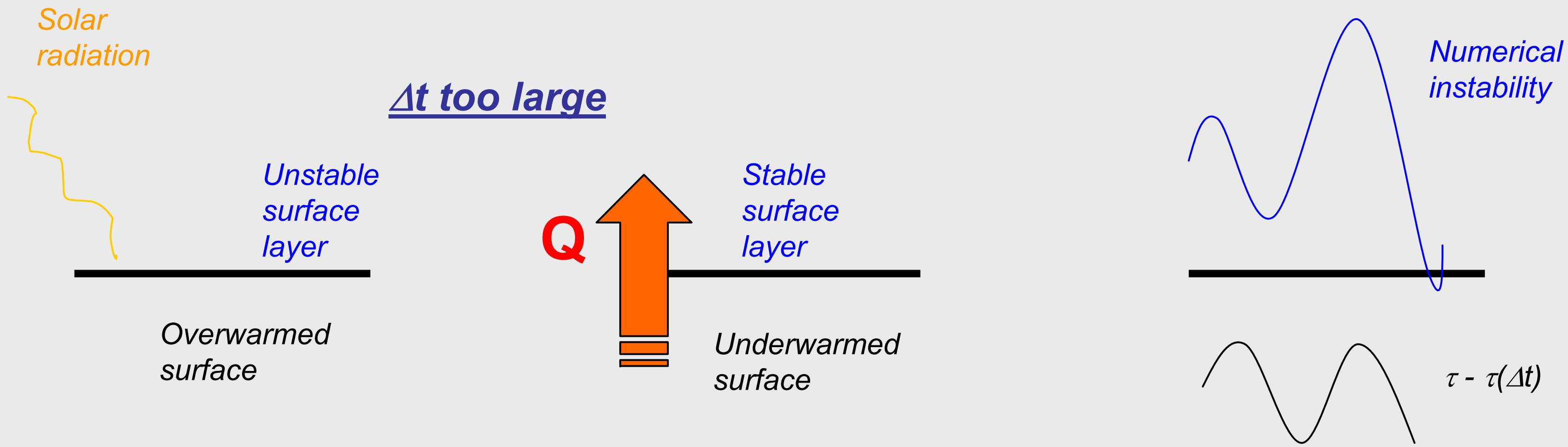


Mellor-Yamada
TKE generation equation

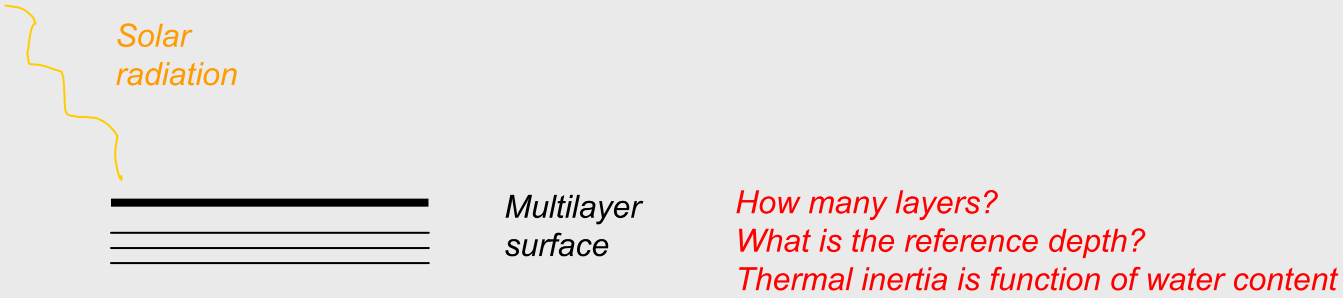
Hong-Pan
Non-local advection scheme

PBL parameterization
(numeric problems)

Temperature oscillations on the surface



Уменьшение шага по времени ограничено техническими возможностями
Фильтрация колебаний имеет формальный подход



Microphysics parameterization
(numeric problems)

<u>Water budget scheme</u> (*Kuo, 1965; Kuo, 1974*)

Assumption: convection is uniquely associated with convective precipitation and determined by large-scale convergence

$$P = \left(1 - b\right) \int_0^{top} \left(\frac{\partial \overline{\rho q}}{\partial t} \right)_h dz$$

P – precipitation on surface,
ρq – mean water content in a layer,
h – layer depth,
b –Kuo parameter, which determine a part of total water converting into precipitation.

<u>Shortness</u>:

Available potential energy is not taken into account => positive feedback convection intensification ➔ water convergence intensification ➔ convection intensification ➔ … ➔ overestimation of convective precipitation while underestimation of stratiform (large-scale) precipitation

Microphysics parameterization

(numeric problems)

Adjustment schemes (*Manabe and Strickler, 1964; Betts, 1986, …*)

Assumption: adjustment of unstable atmospheric state to the *reference* profile occurs during a certain time scale (1 hour for the deep convection, 3 hours for the shallow convection)

$$\left.\frac{\partial T}{\partial t}\right|_{conv} = \frac{T^{ref} - \overline{T}}{\tau} \qquad \left.\frac{\partial q}{\partial t}\right|_{conv} = \frac{q^{ref} - \overline{q}}{\tau}$$

τ- convective adjustment time scale
T^{ref} – reference temperature profile,
T – temperature profile at the start point,
q^{ref} – reference humidity profile,
q - humidity profile at the start point.

Shortness
Reference profiles

Microphysics parameterization
(numeric problems)

<u>Mass flux schemes (</u>see overview by Bechtold, 2007**<u>)</u>**
(Fraedrich, 1973; Arakawa and Schubert, 1974; Bougeault, 1985; Tiedtke, 1989; Kain and Fritsch, 1990; Raymond and Blyth, 1992; Donner, 1993; Gregory et al, 1997; Gregory et al, 2000; Wang and Stevens, 2000; Bechtold et al, 2001)

Small Area Approximation (*Wang and Stevens, 2000*)
Mass flux in general is good, but in individual convective cloud is not

Entraining / detraining plume model *(Gregory et al, 1997)*
There is no universally valid formulation of entrainment rate applicable to all convective simulations

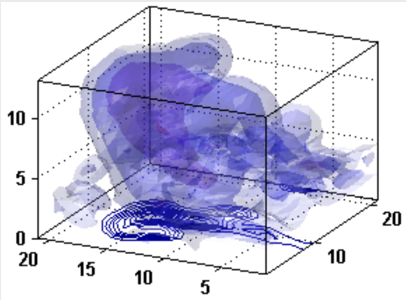
Episodic mixing (*Raymond and Blyth, 1992*)
Stochastic distribution of mixing fraction. Model is very complex and numerically expensive.

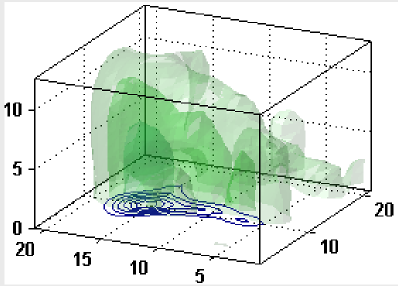
Sensitivity to microphysics parameterizations

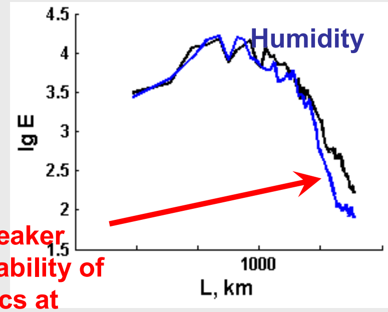
Cloud Water | Rain Water

Grell Convection

Blackadar PBL



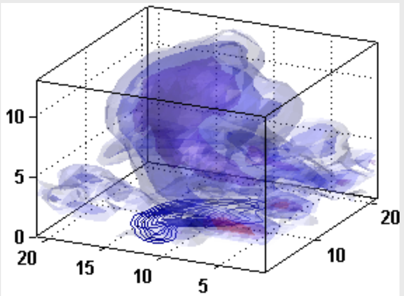


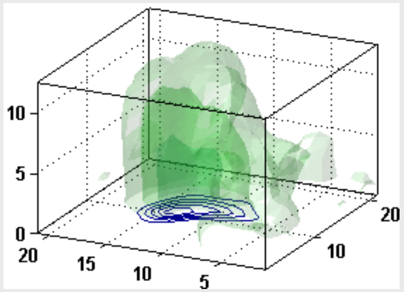


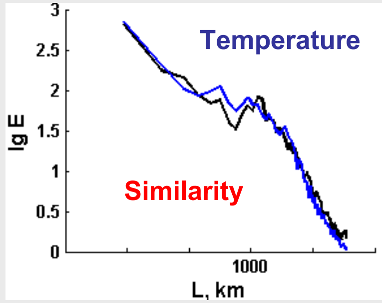
Stronger/weaker spatial variability of microphysics at mesoscales

Kain-Fritsch Convection

Eta PBL





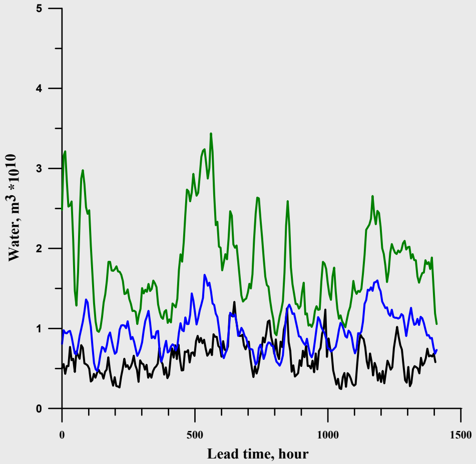


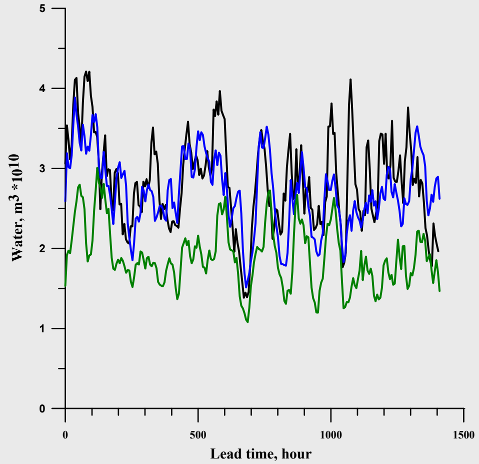
Water content in different aggregation states = Water content in different aggregation states

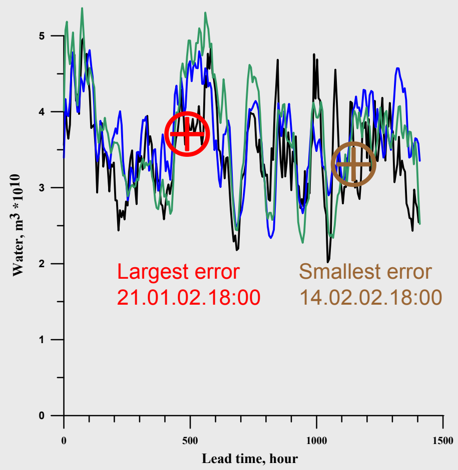
Large scale patterns = Large scale patterns

(*Ivanov et al, 2009*)

Sensitivity to microphysics parameterizations







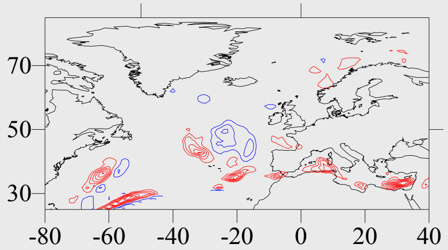
ERA40
Kain-Fritsch
Kuo

Convective Large scale Total

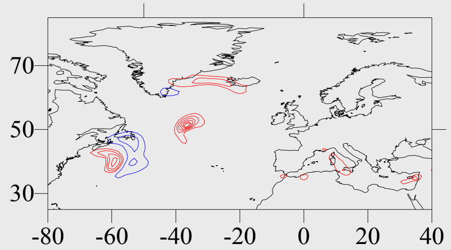
1. The total amount of precipitation over the domain is reproduce in a good agreement with the reanalysis.
2. Water in the model is redistributed between convective and large scale precipitation.
3. The Kuo scheme while providing good *dif* diagnostics for humidity, significantly overestimates convective and underestimates large scale precipitation

(Ivanov et al, 2008)

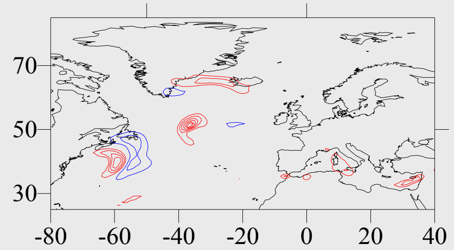
Errors in precipitation modelling



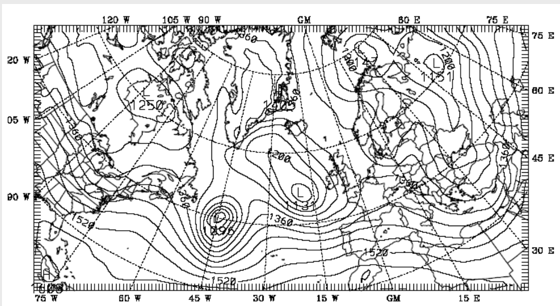
Convective



Large scale



Total



21 Jan 2002 18:00

Overestimation of convective precipitation over the warm ocean.
Phase error of large scale precipitation over an area of intensive atmosphere-ocean interaction.
Areas of both convective and large scale precipitation errors related to two cyclonic patterns with moderate rain over the Atlantic

(Ivanov et al, 2008)

Thanks for your attention