An Overview of Atmospheric Models

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Lecture Outline:

- What are atmospheric model and what are they used for?
- Approach, framework, ingredients and issues.
- Different kinds of atmospheric models.
- Some history and future outlooks.

Lecture materials are chosen for to give an introduction to the subject for MAGS investigators who specialize in areas of study other than meteorology. Canadian MAGS-related models will be used as examples where appropriate.

Atmospheric Numerical Models:
Models of the atmosphere built from fundamental conservation laws governing the physical behavior of the atmosphere, and use numerical methods to obtain the (approximated) solution to the system of coupled governing equations

Applications: NWP, climate prediction, data assimilation, case studies, theoretical & sensitivity studies

Modelling Approach, Framework and Components:

- Physical laws and governing equations
- Numerical representation & solution
- Physical processes parameterization
- Initial conditions
- Boundary conditions

Prognostic Variables Specifying the State of the Atmosphere:

- Horizontal and vertical wind components
- (Potential) temperature
- Surface pressure
- Mixing ratios of water species (vapor, cloud water, cloud ice, rain, snow, etc.)l
- PBL depth or TKE
- Other atmospheric constituents of interest (e.g. chemical species)

Conservation Principles:

- Conservation of momentum
- Conservation of mass
- Conservation of heat (thermodynamic energy)
- Conservation of water and other minor constituents

Framework for Atmospheric Numerical Models

Prognostic Equation: $d\theta/dt = F$

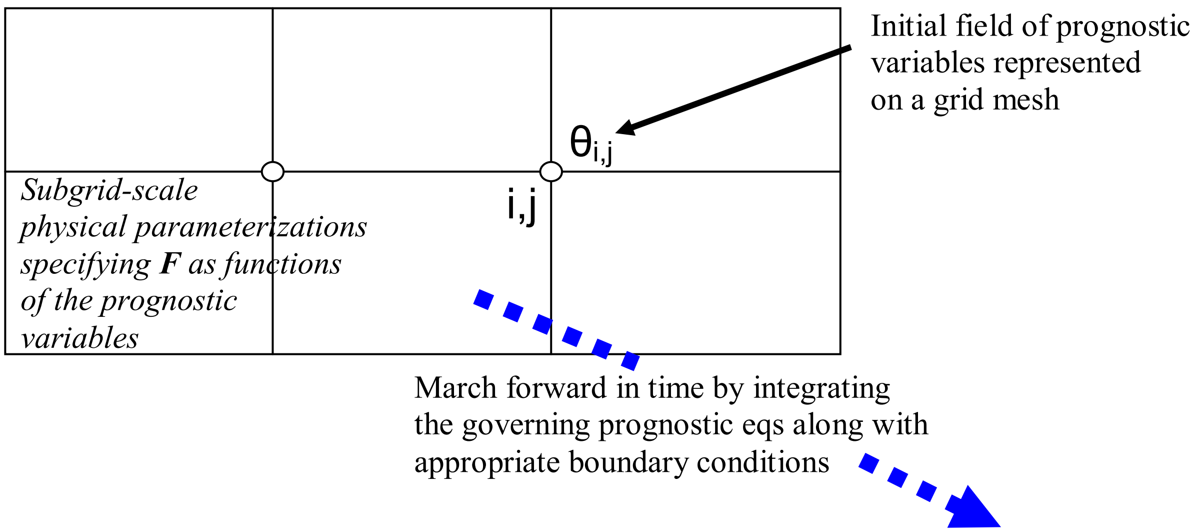

Figure 1: Schematic illustrating the framework for atmospheric numerical models.

Model Equations

- Primitive Equations (PE)- the basic set of eqs derived by using minimal assumptions
  - Prognostic Equations:
    - Horizontal momentum equations (u and v)
    - Vertical momentum equation (w)
    - Thermodynamic equation (θ)
    - Water Species (r_j)
  - Diagnostic Equations
    - Mass continuity equation
    - Equation of state (ideal gas)
    - Sometimes the vertical momentum equation is replaced by the diagnostic hydrostatic equation in models of the large-scale flow.

Vertical Co-ordinates

Most models adopt terrain-following vertical coordinate systems:

- Sigma (P/Ps)
- Eta (eta =(P-Pt)/(Ps-Pt))
- Gal-Chen (Z(X,Y,z) = H * [z - zs(X,Y)] / [H - zs(X,Y)], H=z of model lid
- Hybrid (sigma at lower levels becoming theta or z in upper levels)

Numerical Representation

- **Finite difference**
    - Pointwise representation on a grid mesh
- **Galerkin**
    - Representation of dependent variables by a finite series of linearly-independent basis functions, transforming the PDE into a set of ODE for the coefficients
        - Spectral method
            - orthogonal basis functions (e.g. spherical harmonics)
        - Finite elements method
            - piecewise basis functions that are 0 everywhere except in a limited region

Pros and Cons of the Different Approaches

- **Finite-difference:**
    - Simplicity
    - Nonlinear instability and aliasing problems - could be minimized by using special techniques like Arakawa Jacobian
- **Spectral Method:**
    - More accurate than F-D for same degree of freedom
    - No aliasing problem (as in F-D) since shorter waves are truncated and their interactions are excluded
    - No "polar problem" in global applications
    - "Spectral ringing" (e.g. in mountainous regions)
    - Complexity in implementation and solution
- **Finite-elements Method:**
    - Flexibility in grid structure for irregular domain or variable resolution
    - Complexity in implementation and solution

Time-integration Schemes

- **Eulerian:**
  - Fixed grid points and fields evolve around them
  - *Explicit:* Two-level (e.g., Forward) or Three-level (e.g., Leapfrog)
    - Stringent stability criteria: timestep dictated by phase speeds of fast moving gravity waves
  - *Semi-implicit (SI):*
    - Explicit for advective terms and implicit for linear terms governing fast-moving waves
    - Relaxed numerical stability criteria
- **Semi-Lagrangian (SL):**
  - Fields evolve following fluid particles
  - Chose different set of particles at each timestep so that a regular mesh can be used
  - Relaxed numerical stability criteria
- **Semi-implicit Semi-Lagrangian (SISL)** schemes provide the most efficient method: SI for fast moving waves and SL for advection. The maximum timestep can be chosen as a function of the physics, rather than the stability of the numerical method.

SL & SI schemes requires more computations per timestep - SISL schemes typically provide a 4 -6 fold gain in computational efficiency despite overhead.

Computational Stability

Consider the Linear Advective Equation:

$$\frac{\partial F}{\partial t} = -c\frac{\partial F}{\partial x}$$

Leapfrog Scheme:

$$F^{n+1} = F^{n-1} - c\frac{\Delta F^n}{2\Delta x}2\Delta t$$

Courant-Friedrichs-Lewy (CFL) Stability Criteria:

$$c\Big/\frac{\Delta x}{\Delta t} \le 1$$

i.e. if the true wave speed c is greater than the speed at which information propagates in the numerical scheme, instability occurs.

Implicit Scheme:

$$F^{n+1} = F^n - c\frac{\Delta F^{n+1/2}}{2\Delta x}\Delta t$$

$$F^{n+1/2} = (F^{n+1} + F^n)/2$$

Effectively slows down the wave propagation speed and thereby permitting longer Δt.

Model Physics

- Deep and shallow convection
- Stratiform clouds & precipitation (resolved or large-scale condensation)
- Microphysics
- Surface fluxes
- PBL processes, turbulence & diffusion
- Radiation
- Cloud-radiation interaction
- Gravity wave drag

(Refer to Figure 2)

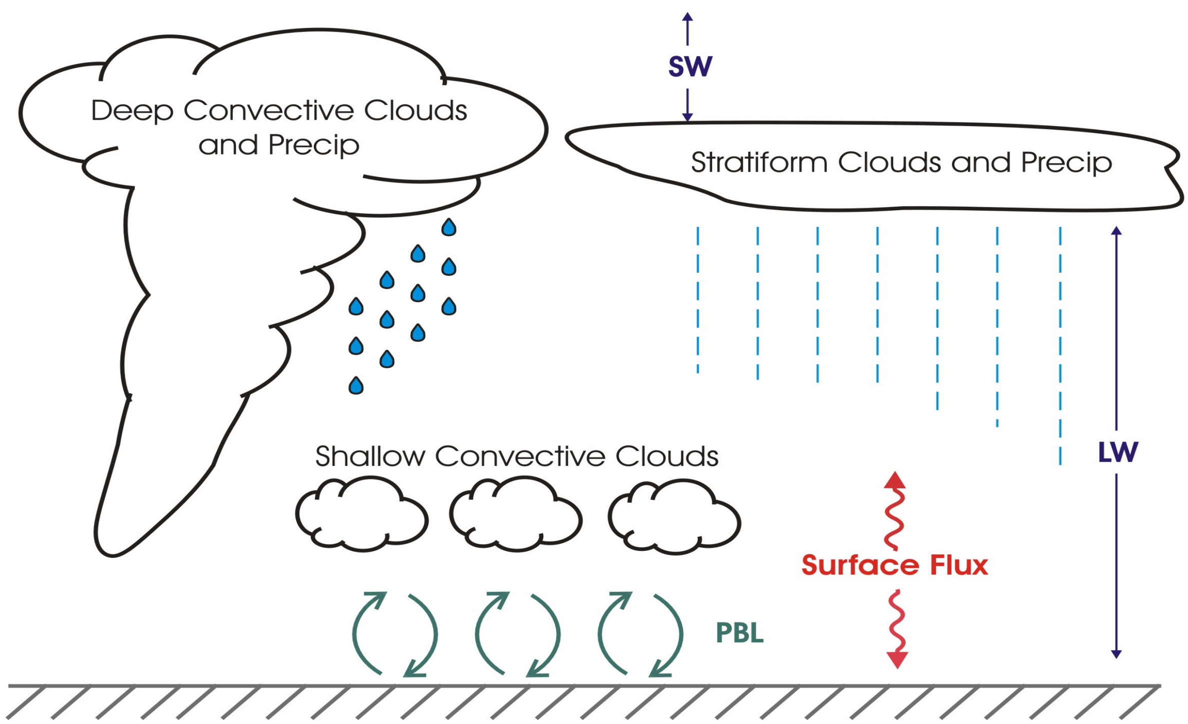

Figure 2: Model physics.

Parameterization: The representation of the grid-scale bulk effects of the subgrid scale processes by using parametric relationships of the prognostic variables. The formulation of the parameterizations could be based on the physical knowledge of smaller scale processes along with some dynamical-statistical upscaling assumptions (physically-based parameterization), or be totally statistically or empirically based.

Table 1: Process parameterizations in the RPN and CCC GCM III model physics libraries (may not be current).

Processes	RPN	GCM III
Radiation	Fouquart & Bonnel - SW Garand – LW	Fouquart & Bonnel - SW Morcrette – LW
Deep Convection	Kuo, Fritch-Chappel, Kain-Fritch	Zhang-McFarlane
Grid-Scale Condensation/ Microphysics	Sunqvist, Tremblay mixed-phase, Kong-Yau bulk	Diagnostic (threshold RH)
PBL/Turbulence	Benoit TKE	Abdella and McFarlane bulk
Gravity Wave Drag	McFarlane	McFarlane
Land Surface	Force-restore/Bucket, ISBA	CLASS

Boundary Conditions

- **Top and lower B.C. needed for all models**
  - Precise specifications of slowly varying surface variables (e.g. SST) not important for NWP but important for climate simulations – the need for fully coupled climate subsystem modules in climate models

Lateral Boundary Conditions and Model Nesting

- Lateral B.C. not needed in global models but essential in LAMs

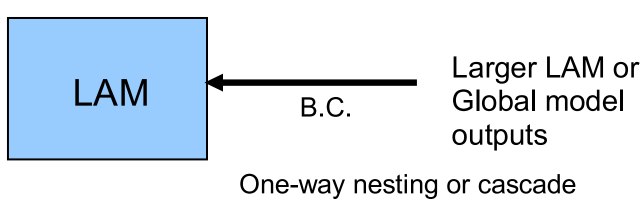

Figure 3: Schematic showing the "forcing" of a LAM by specifying the lateral B.C. with outputs from models with larger or global domains.

- Waves generated inside the LAM must be able to propagate freely out of the lateral boundary or be dampened; otherwise they will be artificially reflected back into the domain and ruin the simulation.

Initial Conditions

- Too little observations for too many grid points
- Different observation sets might not be dynamically consistent with others
- Data Assimilation Systems are used to generate a “best guess” of the 3-D atmospheric state from a limited set of (near concurrent) observations

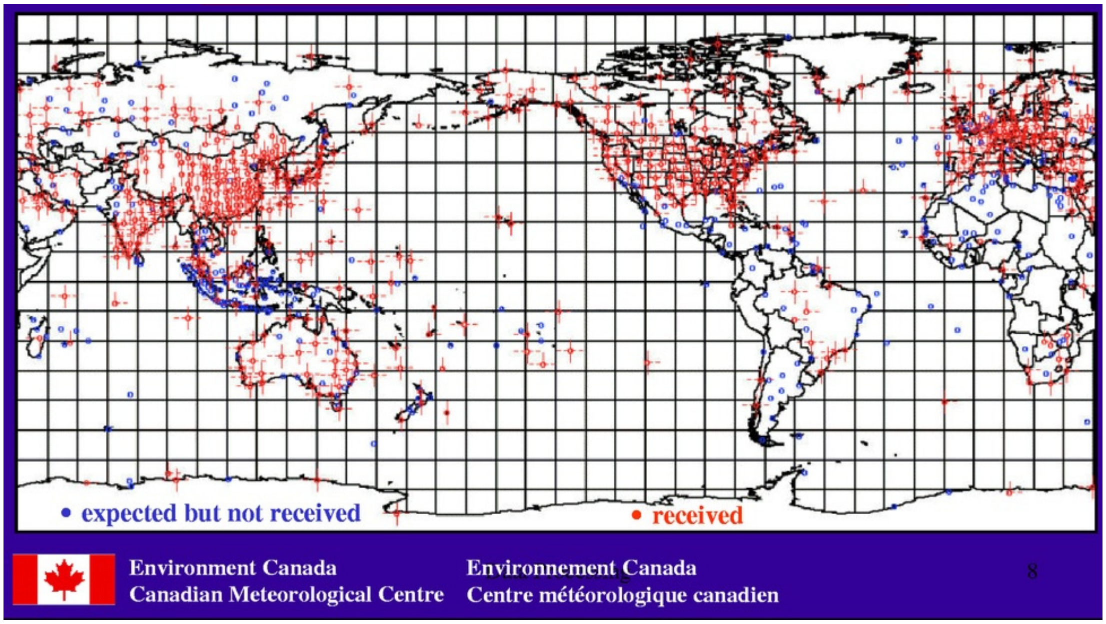

Figure 4: Upper air soundings - June 22 1999 00 UTC ± 3h.

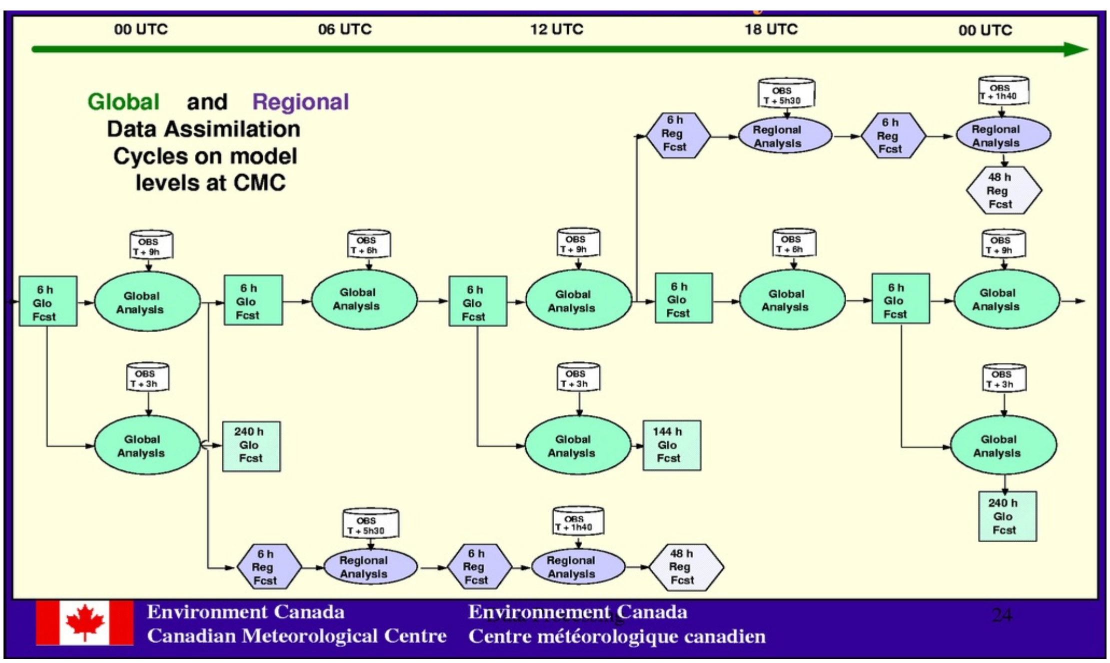

Figure 5: CMC data assimilation cycles.

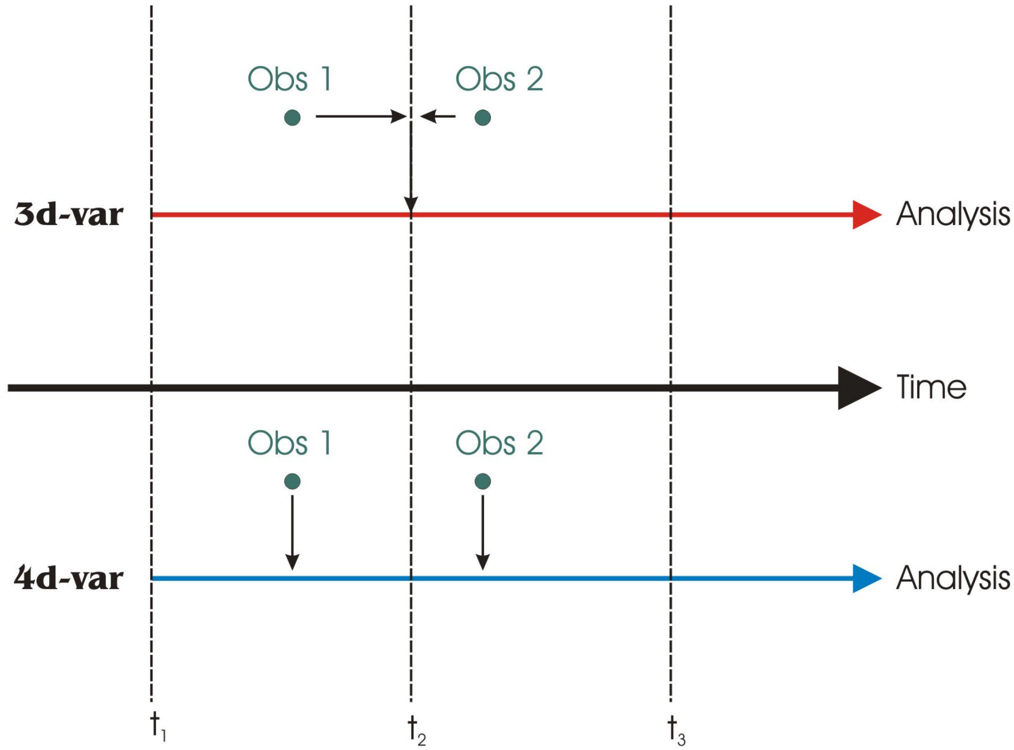

Figure 6: "3-d var" vs. "4-d var" data assimilation.

Errors in Models

- Errors in the initial and boundary conditions (observational or analysis errors)
- Errors in the assumptions used in development of the model equations
- Errors in the numerics
- Errors in the parameterization of subgrid scale processes
- Errors can be random and/or systematic errors
- Different sources of error will have more affect on different models
- Errors in I.C. will have more effects on NWP model than on climate models (more dependent on the accurate specifications of the B.C.)
- Intrinsic predictability limitations (scale dependent) due to the chaotic nature of the atmosphere
- The inevitability of errors from different sources along with the chaotic nature of the atmosphere suggest the need for prediction of uncertainties in the forecast (e.g. by using the ensemble forecast or dynamical-statistical approaches)

Different Types of Atmospheric Models

- Cloud-Resolving Models (CRMs)
- Mesoscale Models
- Numerical Weather Prediction (NWP) Models
- Regional Climate Models (RCMs)
- Global Circulation Models (GCMs)

Considerations in Building Different Types of Models

- **Purposes:**
  - NWP, climate simulation, climate and weather case and process studies etc.
- **Efficiency vs. Accuracy:**
  - NWPs need to be produced in a timely manner but efficiency is not a main concern for a research model
  - Available computer resources?
- **Domain and Resolution:**
  - Global vs. regional
  - Domain must be large enough to protect the main region of interest from boundary effects
  - Resolution should be fine enough to resolve the phenomena of interest
- **Appropriate Model Physics and Assumptions:**
  - Scale (model resolution) dependency of physical parameterizations?
  - Appropriate assumptions used in simplifying the equation sets?
  - All factors are inter-related.

Table 2: Intercomparison of different models (details might not be current).

	MC2	GEM	CRCM	CCCma GCMIII
Regional/ Global	Regional	Global	Regional	Global
Physics Package	RPN	RPN	CCCma GCMIII	CCCma GCMIII
Hydrostatic	N	Y	N	Y
Spatial Discretization	Finite-Differencing	Variable Grid Spacing, 3-D Finite Element	Finite-Differencing	Spectral, finite-element in vertical
Timestepping	SISL	SL, 2-level implicit	SISL	SI
Vertical Coord	Terrain-Following (Gal-Chen)	Terrain-Following (Eta)	Terrain-Following (Gal-Chen)	Terrain-Following (Eta)
Applications	Cloud-scale and mesoscale modelling, regional forecast	NWP, Data Assimilation, Research	Regional climate simulation and prediction, regional climate change scenarios	Global Climate prediction and simulation, climate change scenarios

Effects of Model Configuration on Simulation Results

Comparison of a Frontal System Simulated with MC2 but with different model resolution and physics

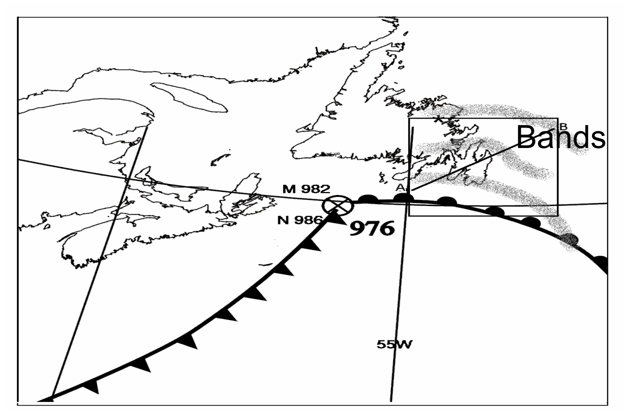

Figure 7: An observed frontal cyclone with embedded mesocale rainbands (shaded).

Cross-section along AB in Figure 7 from simulations with different MC2 configurations. Note how the detailed "band" structures were reproduced in the CRM simulation (Fig. 8) but not in the "GCM-type" simulation (Fig. 9).

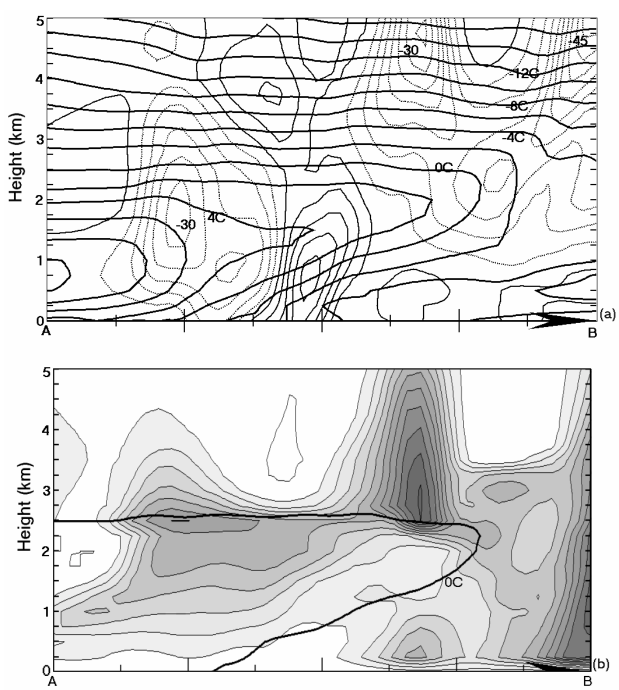

Figure 8: CRM - 10km resolution, detailed microphysics: a) T (thick solid) and Omega (dashed); b) cloud mixing ratios (shaded).

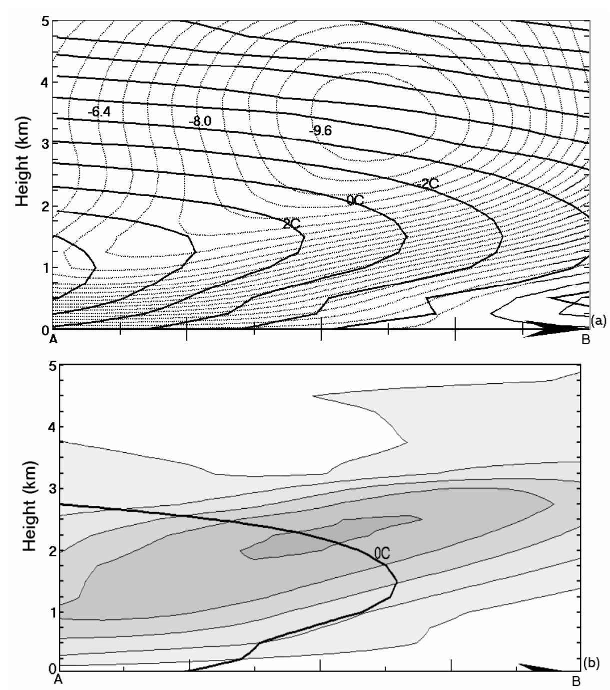

Figure 9: "GCM" - 150km resolution, simple microphysics: a) T (thick solid) and Omega b) cloud mixing ratios.

Putting it all Together

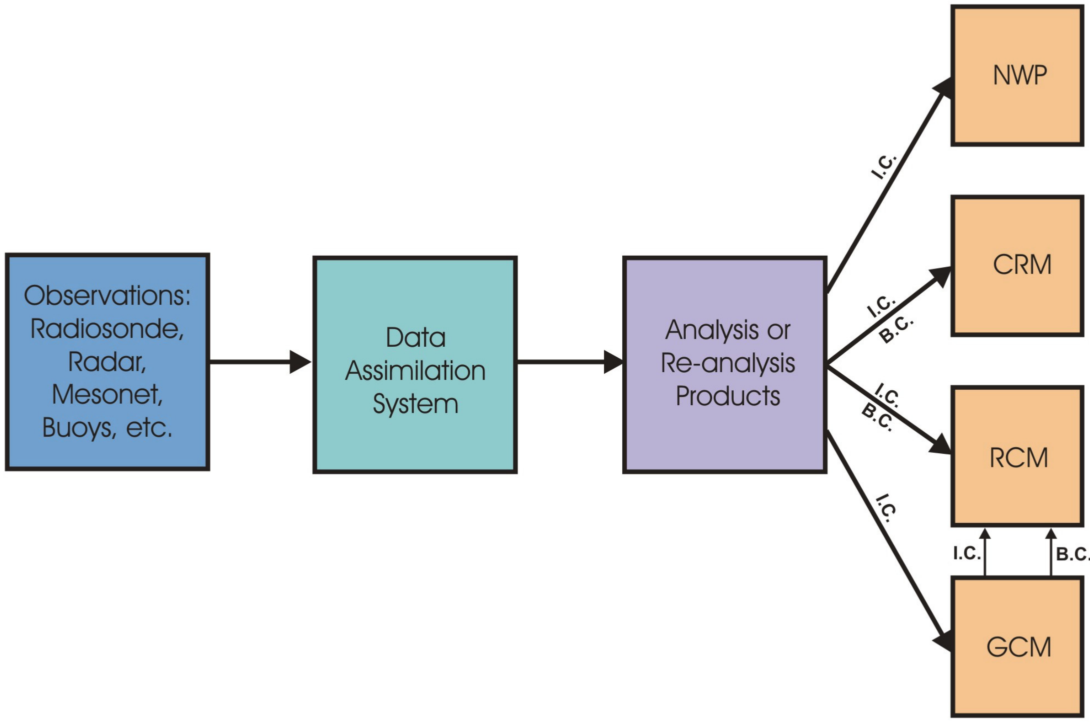

Figure 10: From observations to model simulation/predictions.

A Brief History

Pioneers

- 1904: V. Bjerknes - formulated weather forecasting as an initial-value problem using known basic system of equations and proposed "graphical calculus" method for solution
- 1922: L. F. Richardson - first attempt at carrying out NWP - The "forecast factory"
- 1948: Charney, Fjortoft, and von Neumann - First successful NWP using the ENIAC
- 1955: Norman Phillips – First AGCM

Canadian Developments & Contributions

- Early 60s: Barotropic model (Robert)
- 1965: First successful spectral integration of PE (Robert)
- Late 60s: First implementation and test of SI scheme (Robert)
- 1968: Baroclinic model (Robert)
- 1976: First operational spectral model SPE (Daley)
- Late 70s: Canadian GCM-I based on SPE with modified physics (Boer, McFarlane)
- 80s: Development of SISL methods (Robert, Ritchie et al.)

- 1985: Regional Finite-elements model RFE (Staniford, Daley et al.)
- 1990: Fully compressible SISL mesoscale model MC2 (Robert, Laprise, Benoit et al.)
- 1991: First SISL global spectral model SEF (Ritchie et al.)
- 1995: CRCM – MC2 dynamics + CGCM physics (Laprise et al.)
- 1997: Global Environmental Multi-scale Model GEM (Côté et al.)

Outlooks

- Improved automated code-optimization to fully utilize the powers of massively-parallel machines
- Implementation and testing of modern numerical techniques developed in other areas of studies
- Further research on the implications and applications of ensemble predictions
- "Super-Parameterization" - using embedded CRMS within GCMs to predict bulk effects of small scale features rather than by using traditional parameterization schemes
- Mobile mesonets to obtain detailed observations over regions that are particularly sensible to errors in initial conditions
- Reliable remotely-sensed high resolution 3D-atmospheric fields for initialization and validation of high-resolution models
- Global mesoscale or cloud models

Further Readings

Numerical Modelling Text:

Haltiner, G. J. and R. T. Williams, 1980: Numerical Prediction and Dynamic Meteorology, Wiley and Sons, Inc., New York, 477 pp.

Pileke, R. A., 1984: Mesoscale Meteorological Modelling, Academic Press, New York, 612 pp.

Climate Modelling:

Trenberth, K. (ed.) 1992: Climate System Modelling. Cambridge University Press, 788pp.

Randall D.A. (ed.) 2000: General circulation model development: Past, present and future. Academic Press. 807pp.

Brief history of GCMs:

http://www.aip.org/history/sloan/gcm/intro.html

CCCma GCM:

http://www.cccma.bc.ec.gc.ca/models/models.shtml

Boer, G.J., N.A. McFarlane, R. Laprise, J.D. Henderson, and J.-P. Blanchet (1984): The Canadian Climate Centre Spectral atmospheric general circulation model. Atmos. Ocean, 22, 397-429.

McFarlane, N.A., G.J. Boer, J.-P. Blanchet, and M. Lazare, 1992: The Canadian Climate Centre second-generation general circulation model and its equilibrium climate. J. Climate, 5, 1013-1044.

Information on Operational Models:

http://www.erh.noaa.gov/er/bgm/models.htm
http://www.met.nps.navy.mil/~jordan/mr4323/Lab9_02_nwpsites.html

GEM:

http://www.msc-smc.ec.gc.ca/cmc/GEWEX/regional_forecast_e.html
http://www.msc-smc.ec.gc.ca/cmc/op_systems/global_forecast_e.html

Côté et al., 1998: The Operational CMC-MRB Global Environmental Multiscale (GEM) Model. Part I: Design Considerations and Formulation. Mon. Wea. Rev., Vol 126.

CRCM:

Bergeron, G., Laprise, L., and Caya, D., 1994: Formulation of the Mesoscale Compressible Community (MC2) Model. Internal Report from Cooperative Centre for Research in Mesometeorology, Montréal, Canada, 165 pp.

Caya, D., R. Laprise, M. Giguère, G. Bergeron, J. P. Blanchet, B. J. Stocks, G. J. Boer, and N. A. McFarlane, 1995: Description of the Canadian regional climate model. Water, Air and Soil Pol., 82, 477-482.

Caya, D., and R. Laprise, 1999: A Semi-Implicit Semi-Lagrangian Regional Climate Model: The Canadian RCM, Mon. Wea. Rev., 127, 341-362.

MC2:

http://www.cmc.ec.gc.ca/rpn/map/mc2_map_mirror/Model/model.html
http://limex.meteo.mcgill.ca:8080/badri/mc2.html

Benoit, R., M. Desgagne, P. Pellerin, S. Pellerin, Y. Chartier and S. Desjardins, 1997: The Canadian MC2: A semi-lagrangian, semi-implicit wide-band atmospheric model suited for fine-scale process studies and simulation. Mon. Wea. Rev., Vol 125

Data Assimilation:

http://www.cmc.ec.gc.ca/cmc/biblios/indexe.shtml (choose NWP Workshop)
http://www.meted.ucar.edu/ist/poes4/frameset.htm
http://www.ecmwf.int/services/training/rcourse_notes/data_assimilation.html

Tutorial on vertical coordinates:

http://www.met.tamu.edu/class/metr452/models/2001/vertres.html