Workshop on Numerical Weather Models for Space Geodesy Positioning

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Room C25 (ADI Room), Head Hall Building

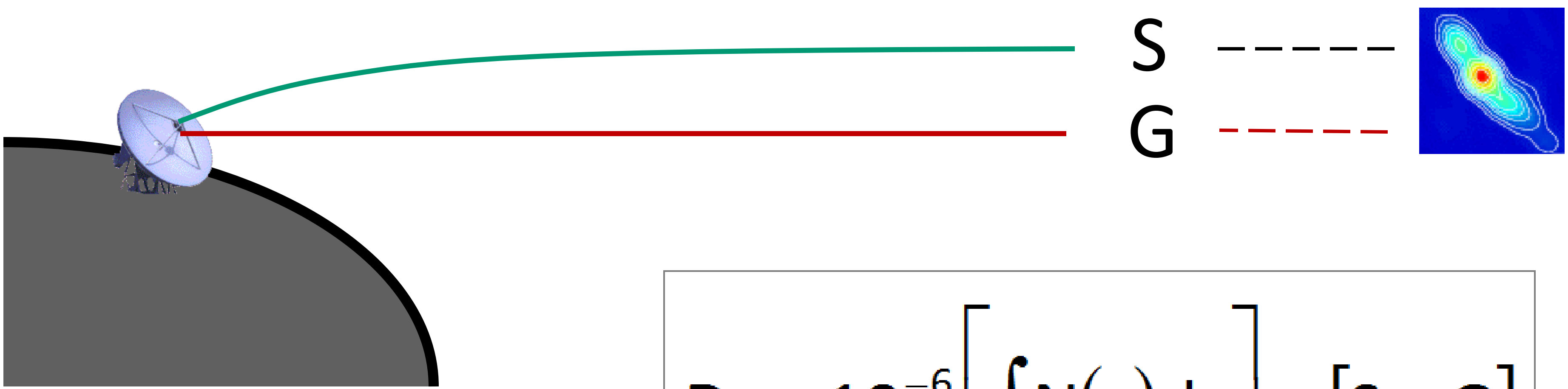
Objectives

- Discuss the use of meteorological numerical information in the modelling of neutral-atmospheric delay
- Discuss a few efforts at UNB

Opening and Welcome

- Program:
  - 9:00 – Opening and Welcome (*Marcelo Santos*)
  - 9:10 – The troposphere: the problem, its modelling and its mapping (*Richard Langley*)
  - 9:35 – Measurements, Water Vapour Radiometer, and applications (*Peter Dare*)
  - 10:00 – Introduction to NWP models (*Marcelo Santos*)
  - 10:25 – Coffee break
  - 10:40 – GEM Numerical Weather Models (*Marcelo Santos*)
  - 11:05 – A snapshot at UNB Ray-tracer (*Felipe Nievinski*)
  - 11:30 – UNB-VMF1: motivation, status and future (*Landon Urquhart*)
  - Monday/Tuesday, room E-3A: discussions on ray-tracing and UNB-VMF1

Troposphere delays



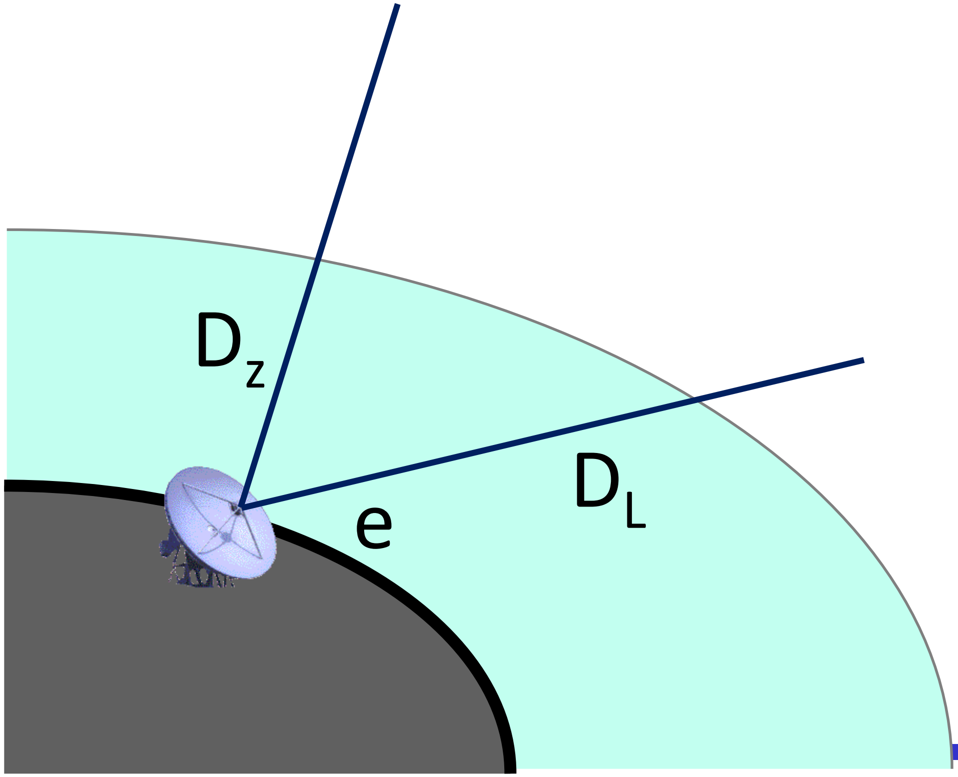
$$D_L = 10^{-6}\left[\int_S N(s)\,ds\right] + \left[S - G\right]$$

E.g., pressure, temperature, and humidity from numerical weather models

Boehm et al., 2011

Troposphere delays

$$D_L(e) = D_z \cdot m(e) = D_{zh} \cdot m_h(e) + D_{zw} \cdot m_w(e)$$



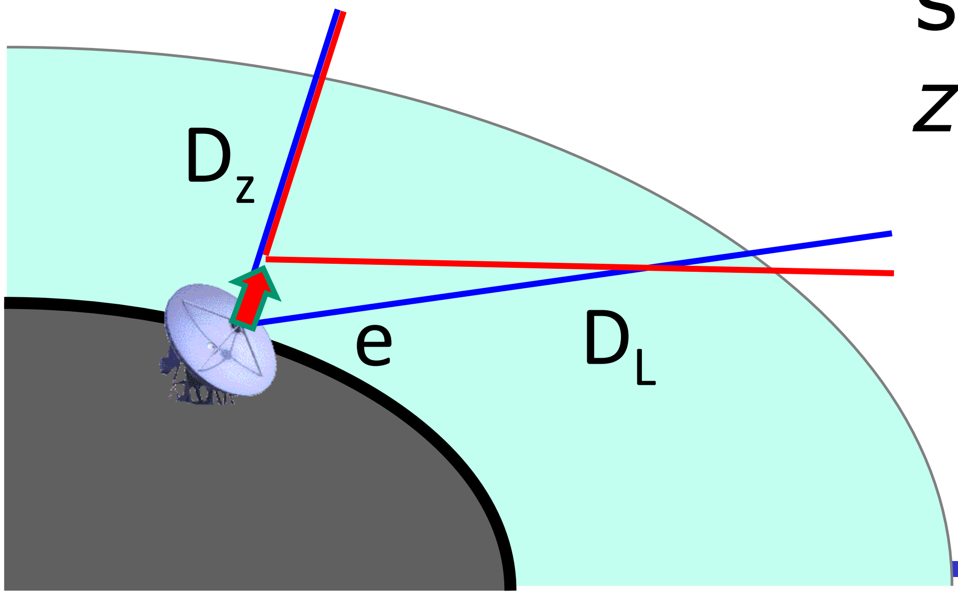
+ gradients

Boehm et al., 2011

Zenith delay – clock - height

$D_L(e) = D_z \cdot m(e)$

$D_L(e) = D_z' \cdot m(e)'$



Partial derivatives:

clock: = 1

height: = sin(e)

zenith delay: ≈ m(e)

Boehm et al., 2011

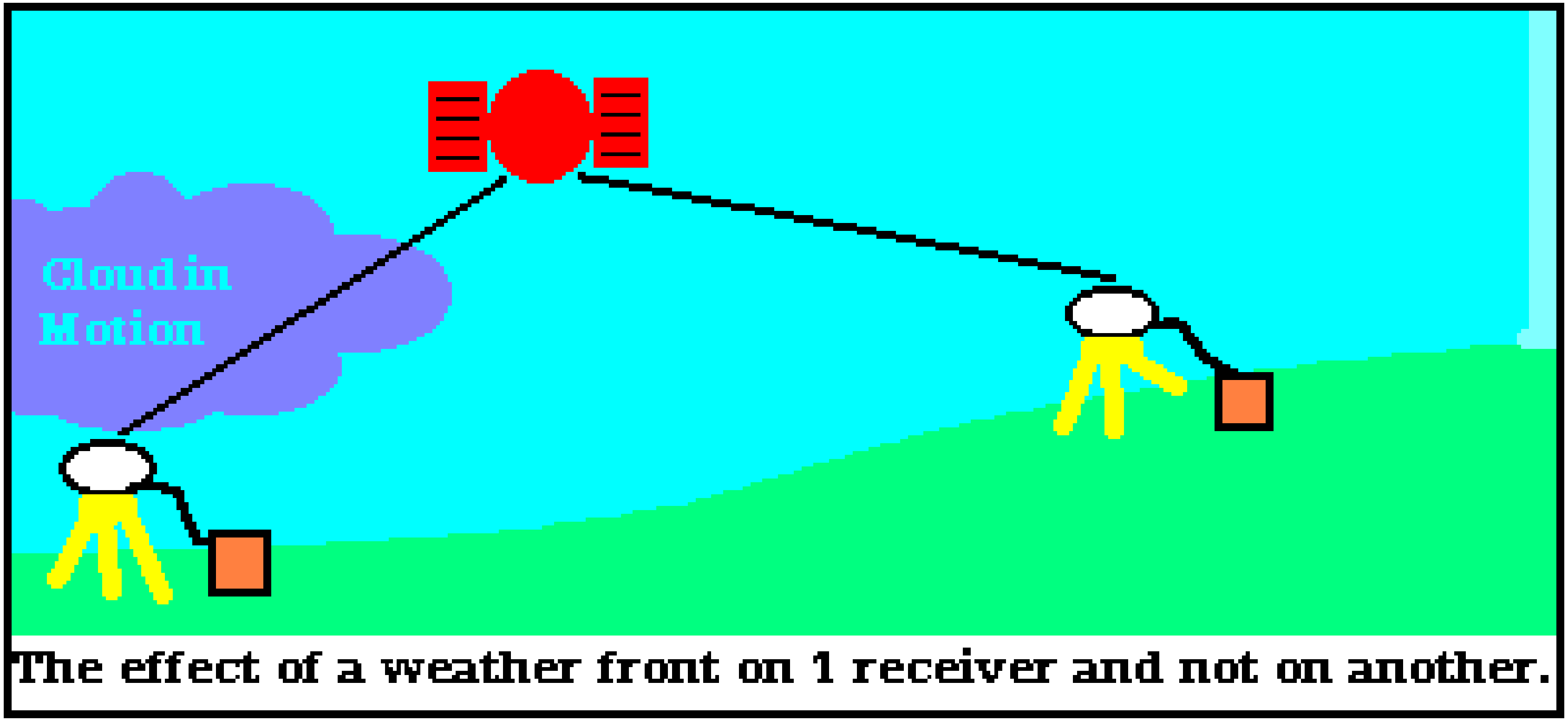
Rule of thumb

- The station height error is about 1/5 of the troposphere delay error at the lowest elevation (5°). (*MacMillan and Ma, 1994*)

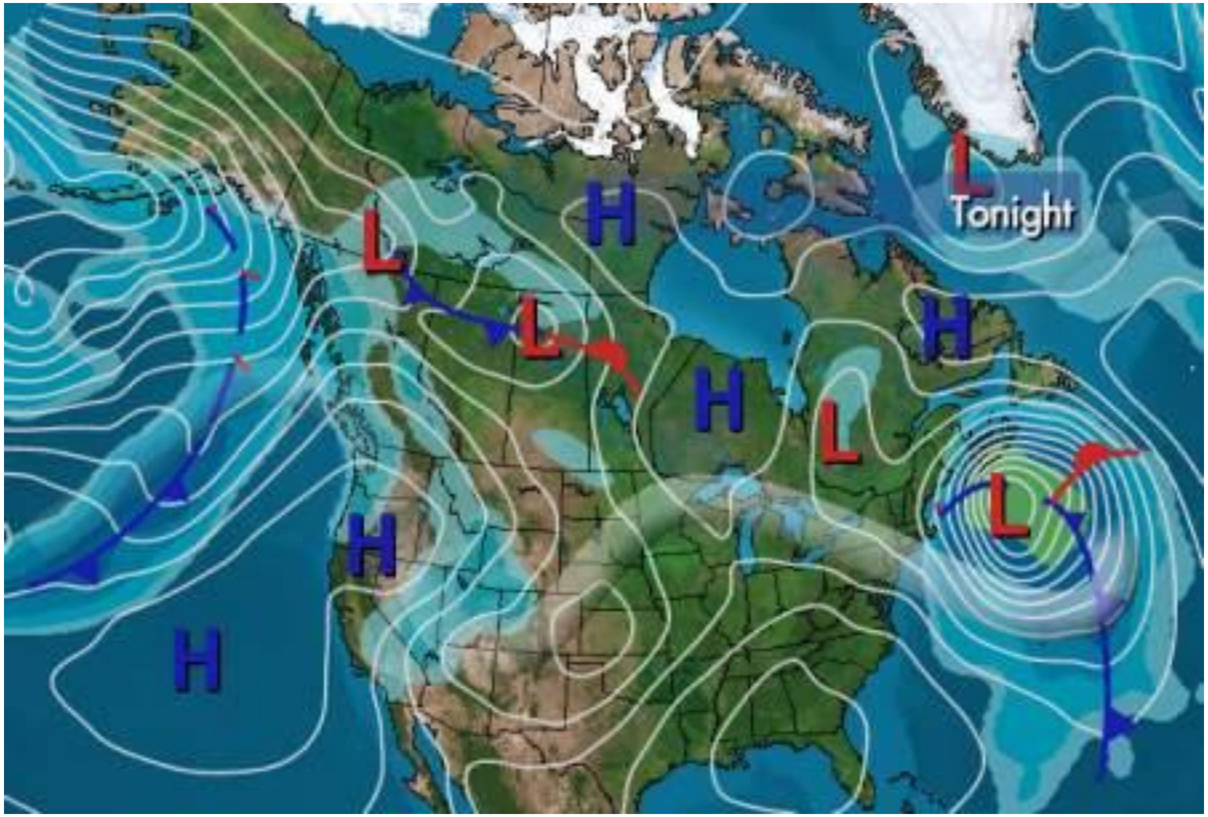
Boehm et al., 2011

Variability in weather conditions

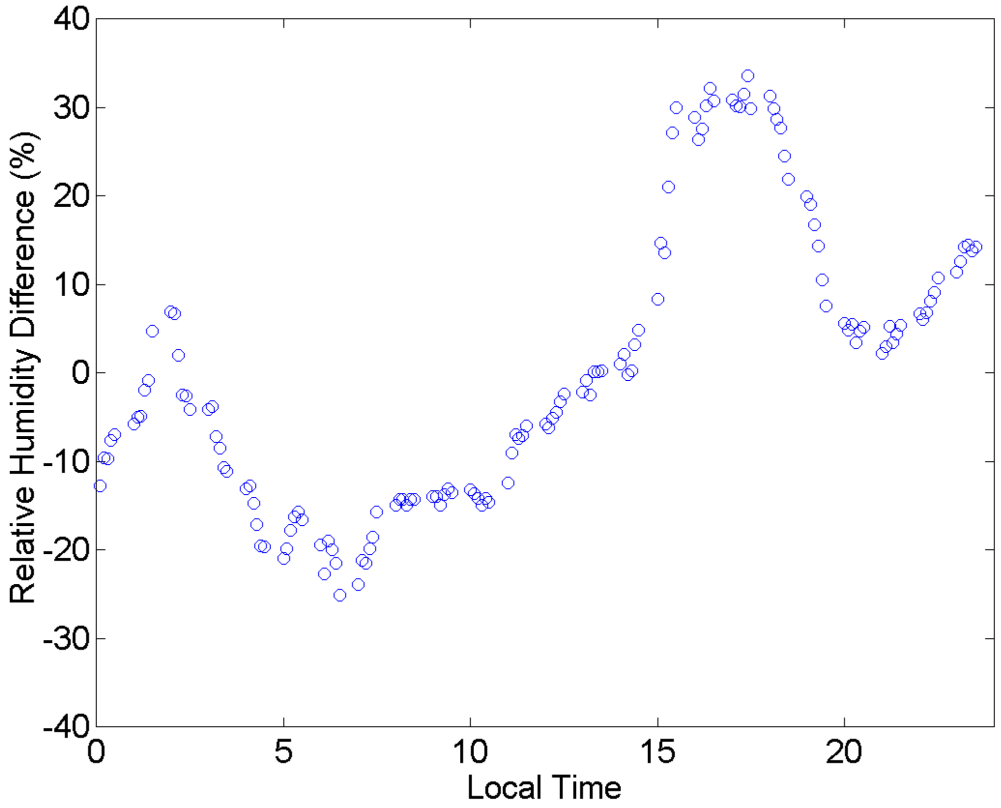
The issue of azimuthal dependency - gradients



Snapshot on 18 February, 2004 weather map

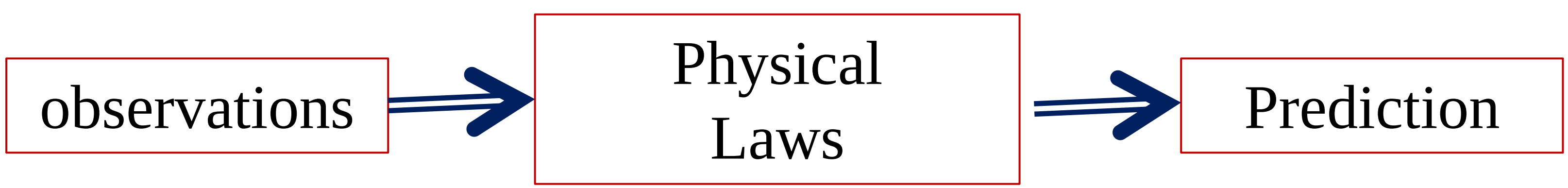


18 February, 2004: St. John- Digby



Numerical Weather Prediction (NWP) Model

- Three dimensional representation of the atmosphere structured as a series of pressure levels covering a grid area.
- Based on the principle that if the present state of the atmosphere and the laws that govern the atmosphere are known then the evolution of the atmosphere can be forecasted into the future.



NWP Limitations

1. Errors in the assumed state of the present atmosphere will propagate and amplify in the forecast.
2. Errors exist in how the theoretical laws that govern the behaviour of the atmosphere are modelled and applied.
   - ✓ Particularly relevant to the estimation of tropospheric delay are errors in the modelling of water vapour
3. The model is limited by grid resolution.
   - ✓ A larger scale model, i.e., smaller grids size, will better represent smaller events and phenomenon
4. The model is limited by spatial resolution.
   - ✓ Unequal distribution of input data

Santos, 2011
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Assimilation

- Process during which the model is updated periodically with quality controlled meteorological data collected globally from a variety of sources including, but not limited to:
  - meteorological observations at the earth's surface and in the air column by sensors such as radiosondes;
  - meteorological stations mounted on platforms such as aircraft, vessels, and buoys;
  - networks of ground based meteorological and GPS stations;
  - radio occultation;
  - Other satellite-borne sensors.
- An interpolation scheme must be used to integrate the irregularly spaced observed data into the gridded area covered by the NWP model

Radiosonde

Moving platforms

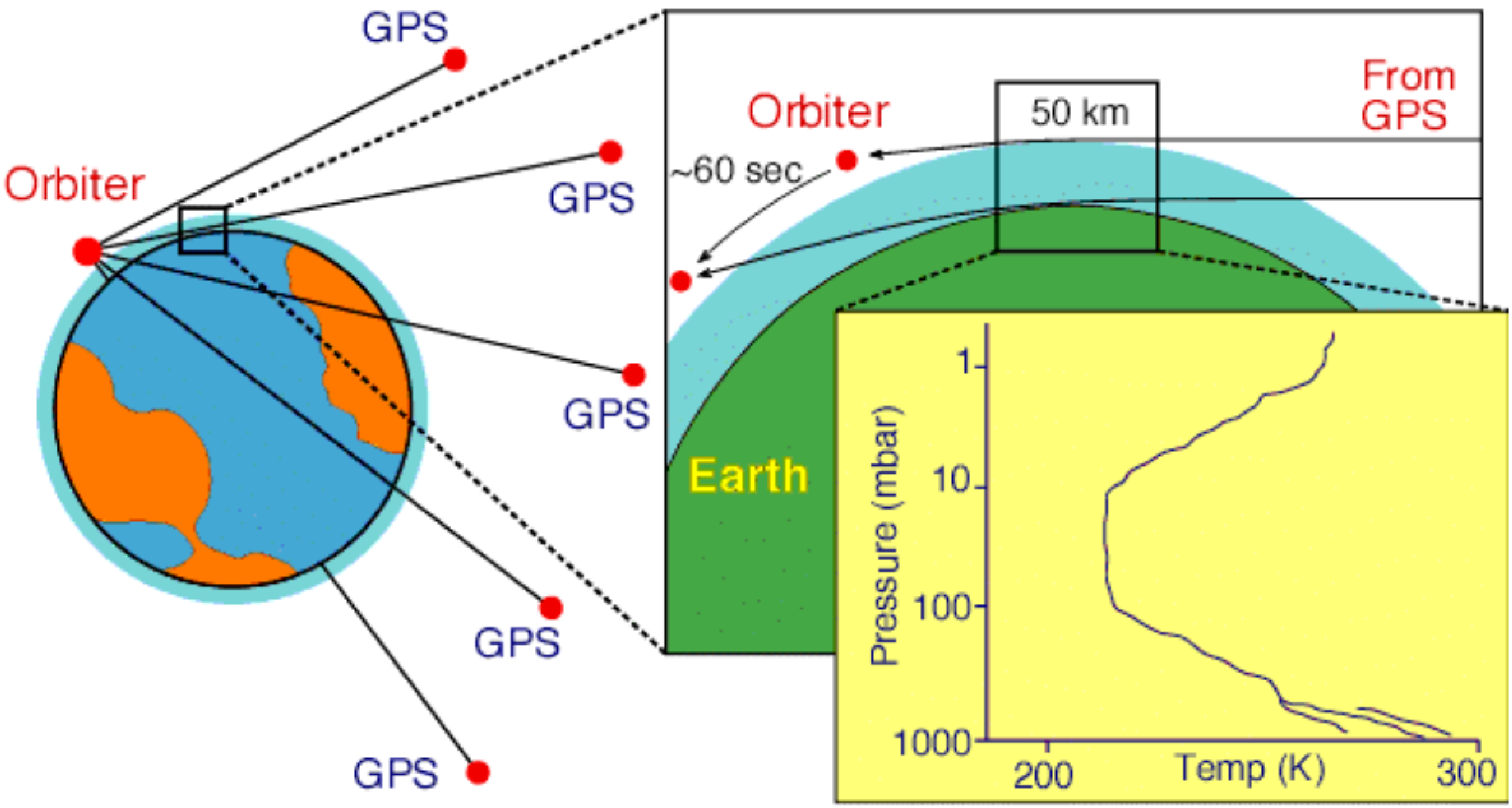
Ships, buoys, aircraft

e.g., Princess of Acadia

Ground networks

SuomiNet

Radio Occultation



Yunck, 2002

Fig. 1 Atmospheric temperature profiling by GPS occultation

Satellite

- All-kind of sensors:
  - Cloud motion winds
  - Surface winds – Scatterometer
  - Microwave - temperature and water vapour
  - Infra-red clear sky temperature and water vapour

How much data involved?

Terrestrial based	
Surface synoptic and ships	31,497
Data buoys, drifting and moored	8,694
Aircraft	52,557
Radio sonde	645
Balloon winds	1,452
Total terrestrial	94,845
Space based	
Cloud motion winds	262,132
Surface winds - Scatterometer	505,140
Microwave - temperature and water vapour	799,644
Infra-red clear sky temperature and water vapour	611,839
Total space based	1,730,253
Total all data Note	1,825,098

For ECMWF

- ECMWF data monitoring pages: http://www.ecmwf.int/products/forecasts/d/charts/monitoring/coverage/dcover!synop-ship!00!pop!od!mixed!w_coverage!latest!/

Global Environmental Multiscale (GEM)

- is the NWP model produced by the Canadian Meteorological Center of Environment Canada.
- Global and Regional operational runs of model are produced daily and disseminated to the public via the World Wide Web.
- The global model covers the entire globe and is used for long-range weather forecasting.
- The regional model is applicable only for short-range weather forecasting in North America.
- Special, high-resolution models produced whenever needed (e.g., over BC during the 2010 Winter Olympic Games).

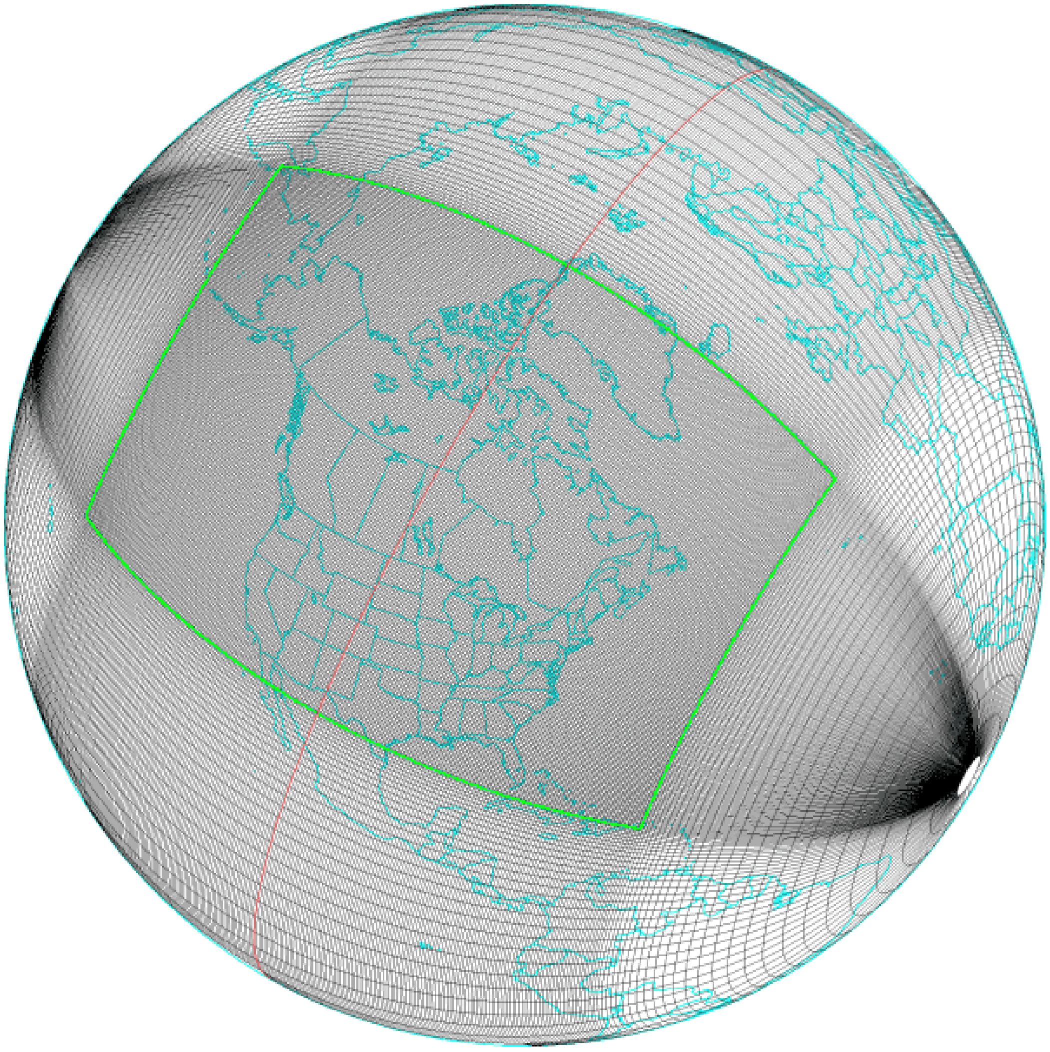
Regional GEM operational model

- Produces an analysis and 48 hour forecast twice daily at 00 Z and 12 Z.
- Each of the Regional model runs begins as a trial field based on the Global model run followed by an analysis "spin-up" cycle where observed data is fed into the model to produce a regional analysis and a 6 hour forecast in the assimilation process.
- Upon completion of the 12 hour spin up cycle, the regional operational model run is produced with an analysis for time T and a 48 forecast. The forecast is produced in 1 hour increments but is only made available to the public in 3 hour increments

Regional GEM grid

- The Regional GEM model is based on a non-uniform grid with a resolution of 15 kilometres at the central core.
  - upgraded on 18 May 2004 from a 24 kilometre grid
- The dataset covers a 501 x 399 Polar-Stereographic grid that covers most of North America and adjacent waters (see next slide).
- Now, covers a 493 x 399 grid (GRIB2).
- There is also a low resolution regional model.

Regional GEM grid



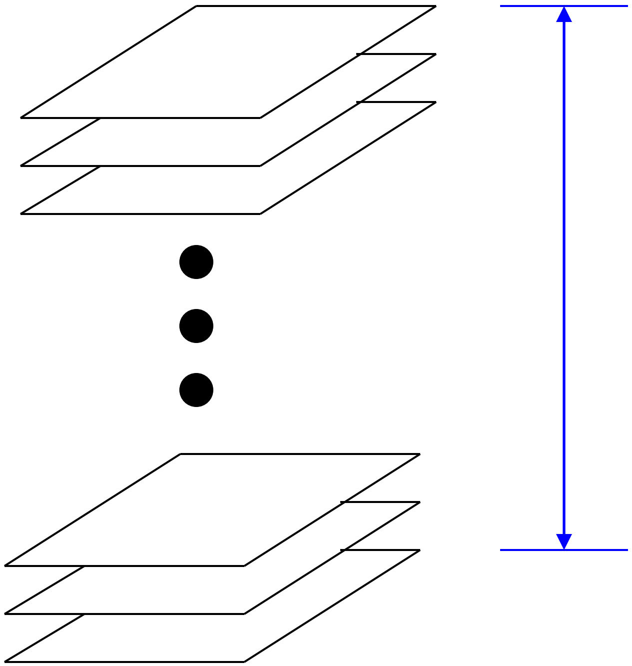
CMC (2002)

Grid nodes at 20 km spacing

Regional and Global GEM grid

- The grid is comprised of 28 levels stacked vertically (at pressure levels 50, 100, 150, 175, 200, 225, 250, 275, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 875, 900, 925, 950, 970, 985, 1000, and 1015 millibars) extending from an equi-potential representation of the earth's surface to a virtual altitude of 30 kilometres. The regional model contains 30 meteorological variables including parameters such as wind speed, temperature, and relative humidity

NWP model



28 isobaric levels for temperature and specific humidity

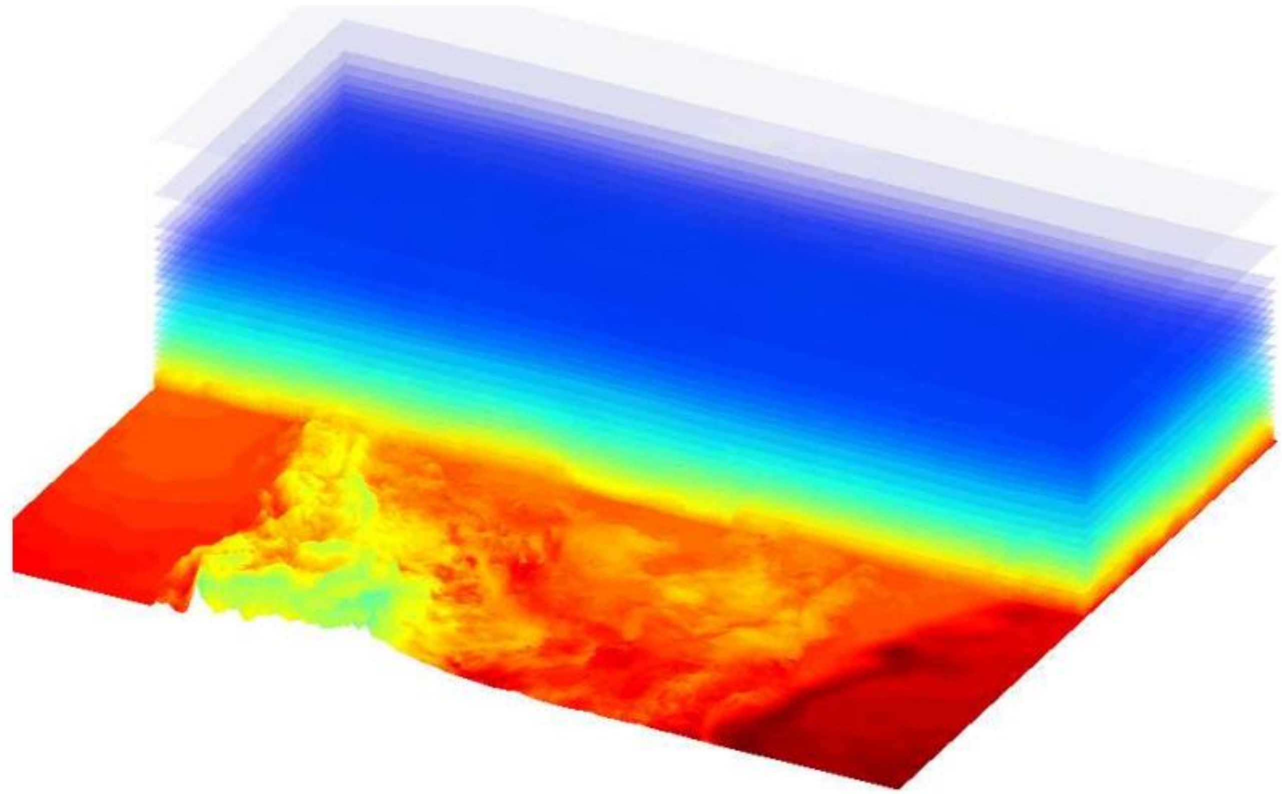


Figure 3: 3-dimensional refractivity field (unitless), as given by the Northern half of the GEM NWM. Height exaggerated 100 times.

Nievinski, 2006

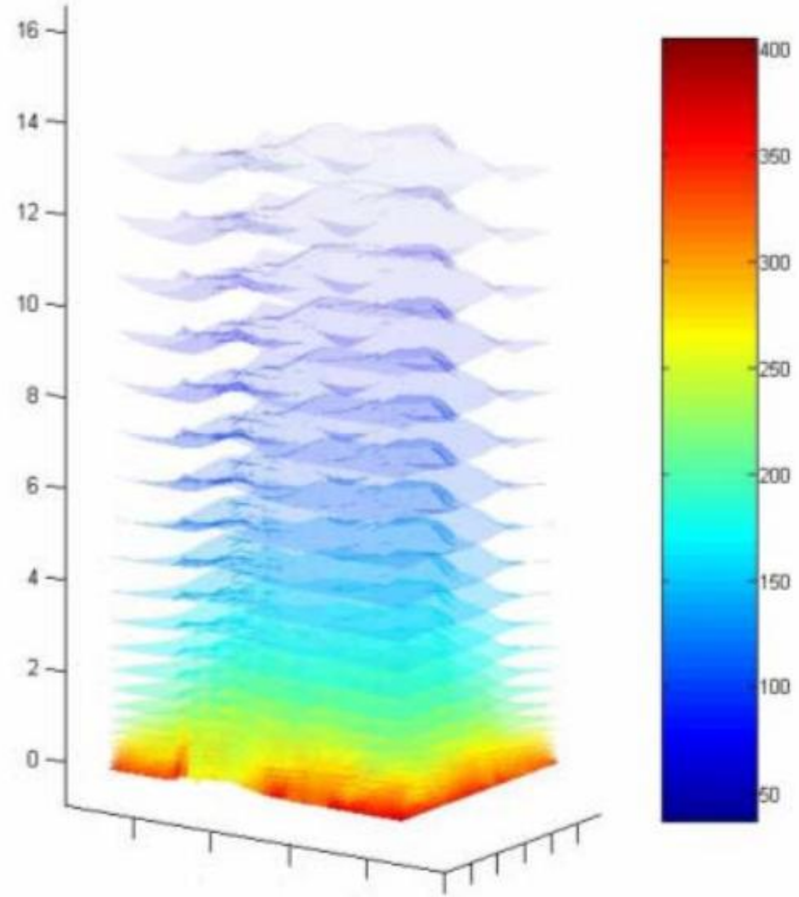


Figure 5: Refractivity field over Canada, May 20, 2005.
(Vertical scale exaggerated 100 times)

Nievinski et al., 2005

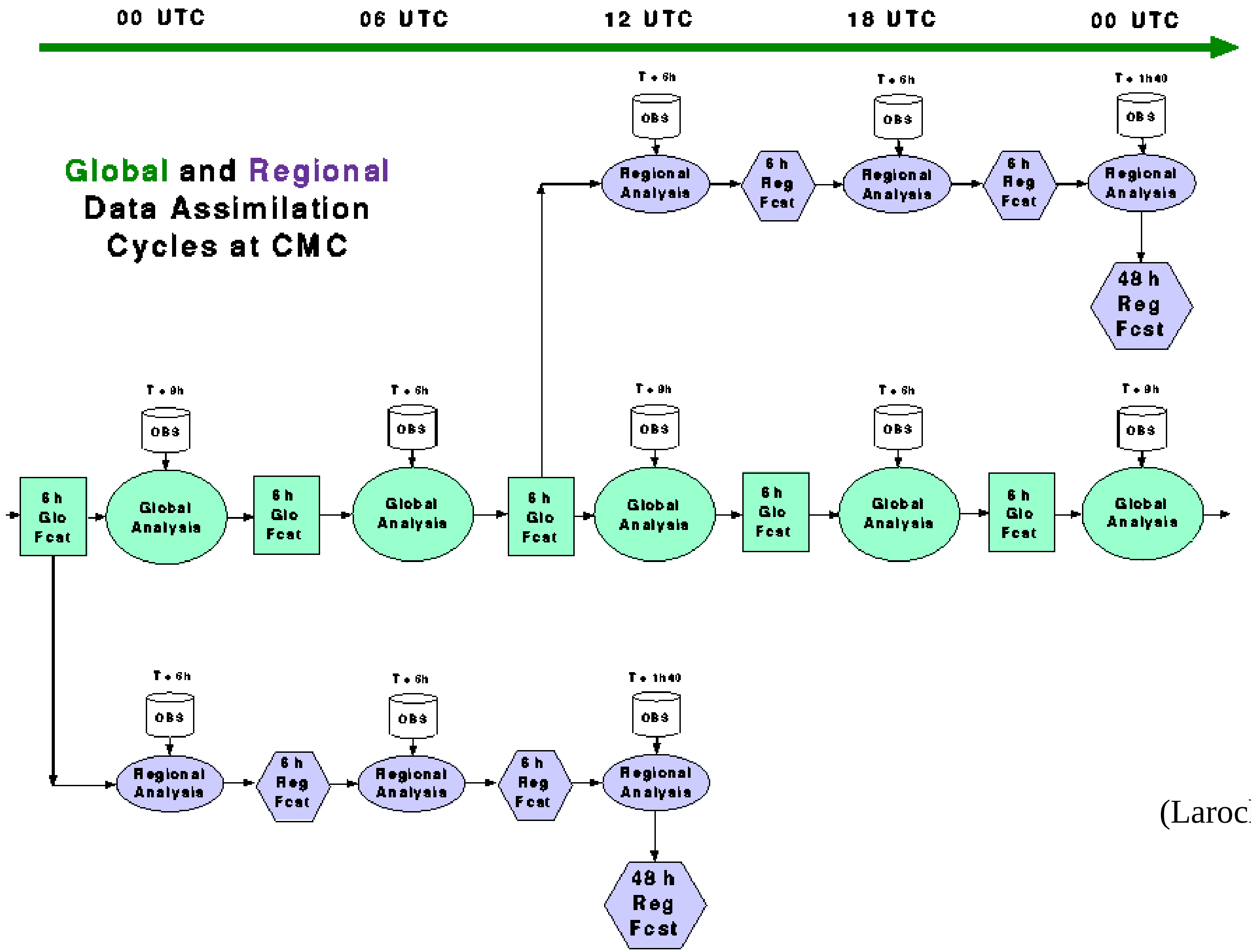
Global GEM operational model

- Run on a Lat-lon grid: 0.3° latitude by 0.25° longitude.
- 00 Z and 12 Z production runs; forecast for 48 hours (12, 24, 36 and 48 hours).
- Available as:
  - Lat-lon grid: 601x301 latitude-longitude grid at a resolution of .6x.6 degrees, which corresponds to about 66 km resolution. The grid is truncated at 90 degrees North and 90 degrees South.
  - Polar-stereographic 30 km global dataset are made available on a 247x200 Polar-Stereographic grid covering North America and adjacent waters with a 30 km resolution at 60°N.
- There is also a low resolution global model.

NWP model

- Analysis field and forecast available.
- Analysis field corresponds to the best fit to the data
- Data of various kinds: aircraft over a path, radio sonde, satellite data, surface observations.
- GEM model: engine to produce the prediction
- Cycle:
  - Analysis
  - Forecast based on the analysis
  - Fit to data
  - New analysis

Global and Regional data assimilation cycles (GEM model)



(Laroche, 1998)

High-resolution runs

- Also produced by the CMC are high-resolution runs of the GEM model with a 10 kilometre grid spacing.
- This version of the model has a finer resolution grid and additional vertical layers (not necessarily available to the public)
- Further information on the global, regional, or high resolution versions of the GEM model can be accessed on the Environment Canada website at http://www.weatheroffice.ec.gc.ca.

Accessibility of the model

- GEM global model data output is made available in GRidded Information in Binary files (GRIB) format.
- GRIB is a globally accepted file data format for the distribution of gridded meteorological data, such as NWP model output.
- The GRIB format allows users to access numerical data directly from weather models for post processing and visualization purposes

Accessibility of the model

- The World Meteorological Organization has issued 3 editions of the GRIB standard.
  - GRIB proper, phased out.
  - The most current edition is GRIB Edition 2, which is in the process of being phased into use in Europe and the United States.
  - CMC employed GRIB Edition 1. In 2010, CMC started offering data in both GRIB1 and GRIB2. Since April 2011, CMC offers data only in GRIB2.

GRIB decoder

- Data in GRIB format can be decoded using freely available software, such as *wgrib* developed by NOAA and the National Weather Service.
- Once the data is decoded, visualization, data extraction, and data format manipulation software such as the Center for Ocean-Land-Atmosphere Studies' Grid Analysis and Display System (*GRADS*) can be employed.

GRIB decoder

- These software products (*wgrib* and *GRADS*) and supporting documentation can be downloaded at http://www.cpc.ncep.noaa.gov/products/wesley/wgrib.html and http://grads.iges.org/grads/ , respectively.
- The decoded GRIB data is also in a format accessible by the user in any programming language or programming tool.

Other NWP models

Model	Description
cmcglb	Canadian GEM Global
cmcreg	Canadian GEM Regional
ukmet	UK Met Office
ecmwf	European Centre for Medium Range Weather Forecasting
jma	Japan Meteorological Agency
dwd	Deutscher Wetterdienst (Germany)
ncep	U.S. National Centre for Environmental Prediction
france	Meteo-France
eta	U.S. North American Model

Modelling Tropospheric Delay with NWP Data

- Tropospheric delays can be obtained directly by integrating the refractivity along the path of the GPS signal through the neutral atmosphere to obtain a slant delay or by integrating vertically to obtain a zenith delay. The equation for refractivity, N, can be expressed in terms of height as:

$$ZTD = 10^{-6} \int_{h_{ant}}^{h_{top}} k_1 R_1 \rho dh + 10^{-6} \int_{h_{ant}}^{h_{top}} \frac{R_d}{\varepsilon} \left(k_2 - k_1 \varepsilon + \frac{k_3}{T} \right) q \rho dh$$

Cove page 30

- where R_d is the gas constant for dry air, ρ is the mass density, ε is the ratio between the gas constant for dry air and the gas constant for water vapour, and q is the specific humidity in kilograms / kilograms.

Modelling Tropospheric Delay with NWP Data

- To express the delay in terms of pressure rather than height one must introduce the hydrostatic equation (Wallace and Hobbs, 1977):

$$\delta p = -\rho g dh$$

- where *g* is gravity in metres/second². The final expression of total zenith tropospheric delay is given as:

$$ZTD = 10^{-6}\int_{h_{ant}}^{h_{top}} k_1 \frac{R_d}{g}\,dp + 10^{-6}\int_{h_{ant}}^{h_{top}} \frac{R_d}{\varepsilon}\left(k_2 - k_1\varepsilon + \frac{k_3}{T}\right)\frac{q}{g}\,dp$$

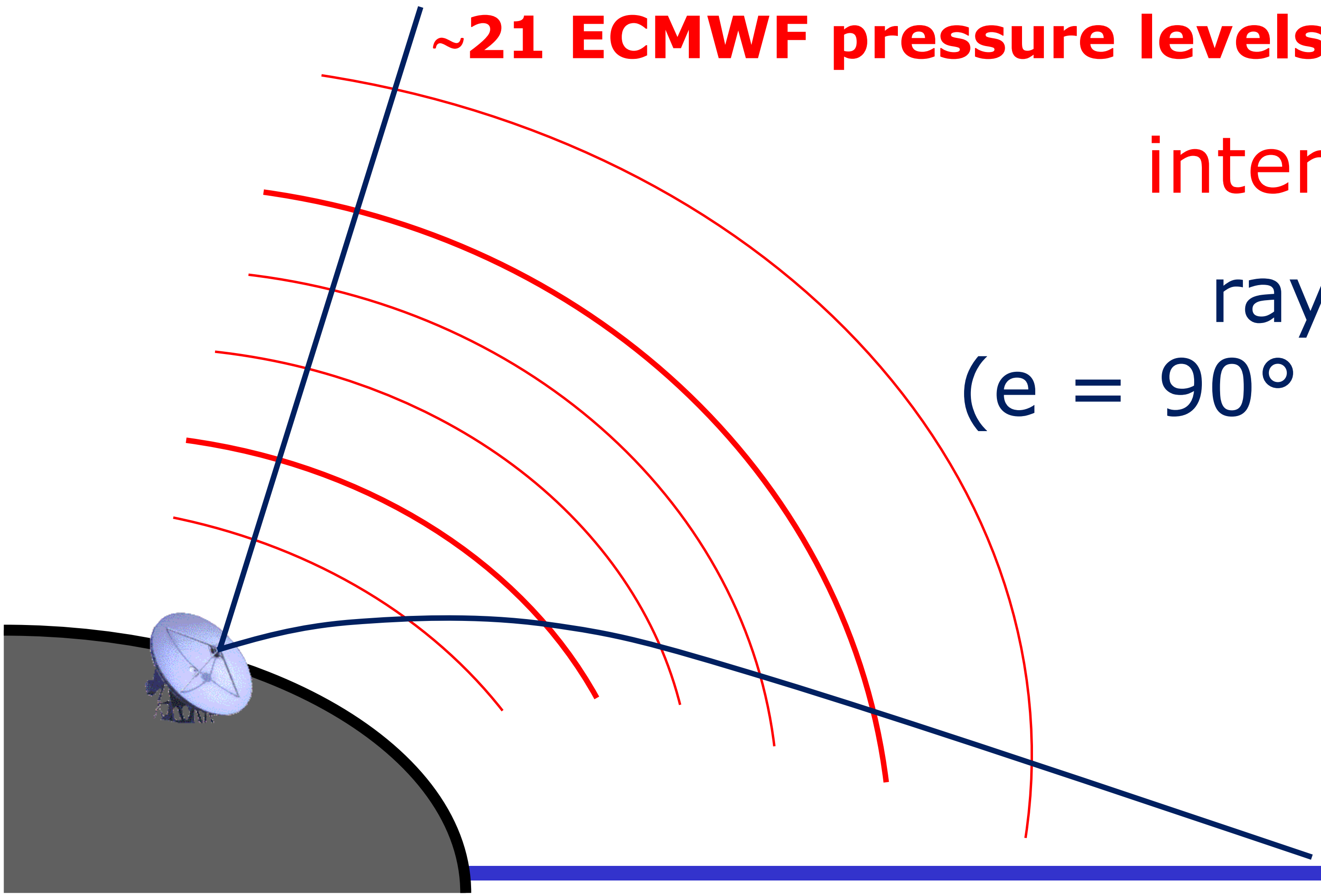
  - The temperature (*T*), pressure (*P*) and specific humidity (*q*) parameters are extracted from the NWP model and a total zenith delay (*ztd*) is calculated at each pressure level.
  - A prediction model is used to estimate the delay for the atmosphere above the top pressure level.
  - The expression of the delay in terms of pressure rather than height is appropriate with use of NWP data since the modelled atmosphere is divided into pressure levels..

Vienna Mapping Functions VMF1

~21 ECMWF pressure levels: T, p_{wv}, h

interpolation

ray-tracing
(e = 90° and e = 3.3°)



Boehm et al., 2011

variable in time and space

$$m(e)=\frac{1+\frac{a}{1+\frac{b}{1+c}}}{\sin(e)+\frac{a}{\sin(e)+\frac{b}{\sin(e)+c}}}$$

ray-tracing

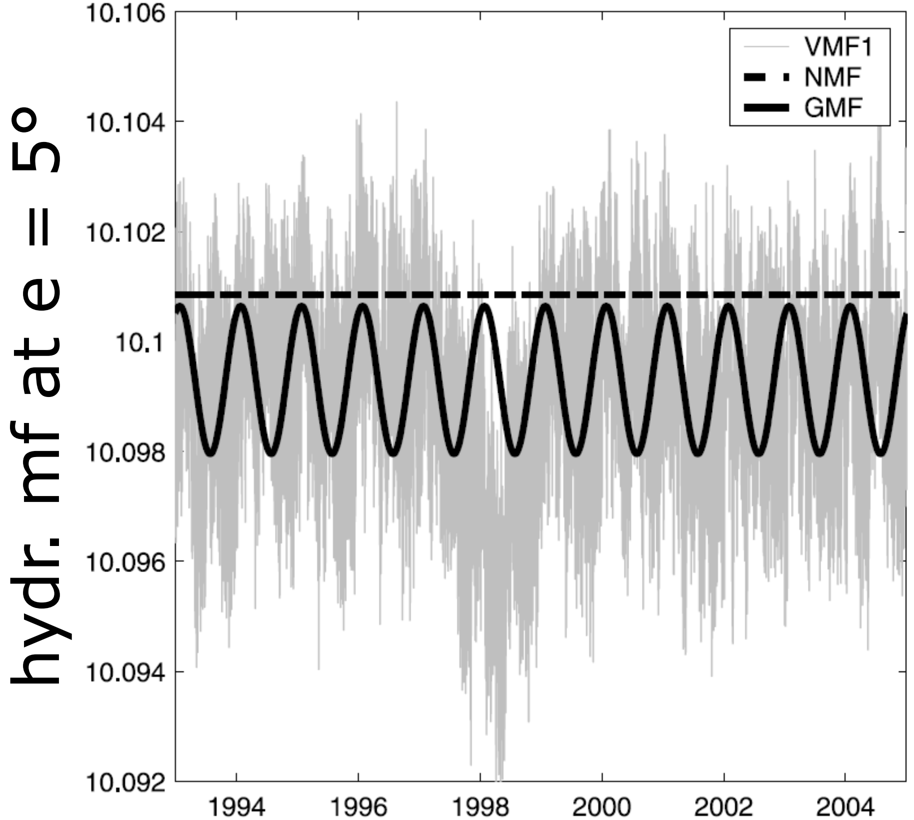
analytical functions

Boehm et al., 2011

Mapping functions

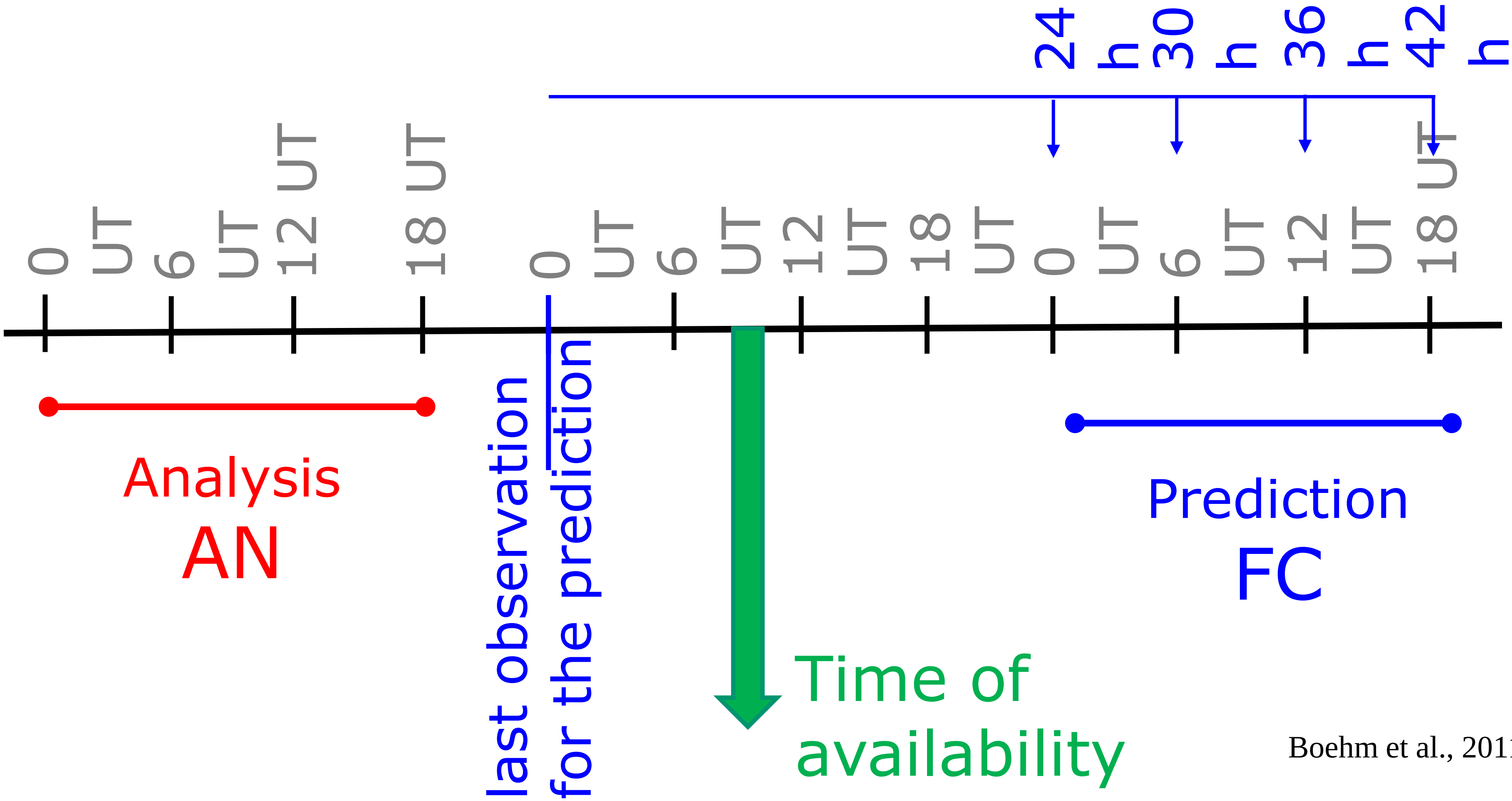
- Vienna Mapping Functions 1
  - from ECMWF data (6 h)
  - Böhm et al. (2006)
- Niell Mapping Functions
  - Niell (1996)
- Global Mapping Functions
  - ‘averaged VMF1’
  - Böhm et al. (2006)

Fortaleza (Brazil)



[Böhm et al., 2006]

Availability of VMF1



Boehm et al., 2011

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Making a Significant Difference

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