The Calibration of the Expression of Refractivity and its Impact in Numerical Weather Prediction

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Topics of this presentation

• Main topic: relationship between refractivity and thermodynamic variables
  – Motivation
  – Our first principles approach

• Short overview of recent performance of GPSRO at Environment Canada
  – Raising the model lid from 10 hPa to 0.1 hPa
  – Recent modification of COSMIC processing
Current role of GPSRO in NWP

- GPSRO data is supposed to be traceable to fundamental standards
- This good traceability is key to its NWP impact: ability to control data known to be biased (radiances, etc)
  - Radiosondes & GPSRO provide anchor points to calibrate data known not to be absolutely calibrated

- GPSRO are the only calibrating data in large portions of the Earth
  - Radiosondes are clustered in NHem, continents
But some symptoms:

• At Environment Canada:
  – Early tests of GPSRO assimilation induced bias wrt RS (previously absent)
    ▪ While searching why, the atmospheric compressibility factor Z was found to lead to noticeable differences in NWP behavior
    ▪ Accounting for Z lead to improved NWP (and operational implementation)
      – Surprising, however, as Z-1 ~ few parts in 10000
  – Main lesson:
    ▪ Good NWP very sensitive to tiny details of anchor (calibrated) data
    ▪ Z was probably not the only issue (there may be others at the level of ~1/10000)

• At ECMWF (Healy):
  – Research on the accuracy of the expression of refractivity
    ▪ Different available expressions lead to significant differences in NWP
    ▪ Confirmed sensitivity to Z

• At NCEP (Cucurull):
  – Tests with several available expressions.
  – NWP results vary:
    ▪ the small differences between expressions are not negligible
GPS RO Impact on 6h forecasts
Radiosondes (winter)

WITH GPS

WITHOUT GPS

27 December 2006–28 January 2007 GPS RO (K4H/C918) vs no GPS RO (K4H/C918)

Northern Hemisphere

Southern Hemisphere

GZ Bias?

SD Bias

T - Td

U

V
GPS RO Impact on 6h forecasts
Radiosondes (winter)

- Very important impact in the Antarctica
- GZ Bias even bigger
- However, TT Bias and TT STD are improved
- Something is wrong with altitudes
- Even so, the effect is small (3-10m at 15 km) i.e. in the range 0.02%-0.1%
The problem

• Certain NWP results are very sensitive to the calibration:
  – Cross-consistency between anchors is needed at levels of $\sim 10^{-4}$
  – There are many subtleties at this level of accuracy
  – Major challenge if anchors are independent

• Consider also that $10^{-4}$ wrt N translates to $\sim 10^{-8}$ in refraction index and signal propagation

• This is very demanding: Do we have this accuracy?

• Currently, NWP is using GPSRO at the edge of the accuracy of the calibration
  – Maybe slightly beyond?
If we prefer not to be at the bleeding edge:

- 2 options:
  - Drop the assumption of absolute traceability of either RS or GPSRO and correct the bias of the other (even if small)
    - One of the promises of GPSRO was that this was not necessary
  - Make an active effort to review the traceability
    - most studies of the underlying physics were not carried out assuming that $10^{-4}$ relative accuracy in \( N \) was at all necessary
    - this will most likely help identify other issues
      - Certainly about GPSRO
      - Maybe about RS, models
        - Radiation bias in RS?
        - Thermal balance in models?
Thoughts and comments

• The compressibility (Z) issues described are related to the model (hydrostatic equation).

• They apply **even at high altitude where the gas is ideal**
  – Because it is not ideal below, even if we are not observing those lower layers.

• The expression of refractivity must also be affected
  – But this applies **only at lower layers** where the gas is not ideal
  – This is less critical, since many other effects obscure Z:
    ▪ More moisture
    ▪ Non-sphericity
    ▪ More noise, low SNR
Thermodynamical expressions

- Expressions now under use are of the form
  \[ N = k_1 \frac{P_d}{T} + k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2} \]

- Function of partial pressures of dry air and water vapor, and temperature
  - Rough values (order of magnitude only!):
    - k1: Electronic polarizability of dry air \( k_1 \approx 77.6 \text{ K/hPa} \)
    - k2: Electronic polarizability of water \( k_2 \approx 70 \text{ K/hPa} \)
    - k3: Dipole polarizability of water vapor \( k_3/T \approx 1300 \text{ K/hPa} \)

- Refractivity is in fact the macroscopic expression of the molecular susceptibility to EM radiation.
  - EM susceptibility can be
    - Electric (most of the susceptibility is electric)
      - Electronic (quite uniform across different conditions, substances and states of matter: k1~k2)
      - Polar (only polar molecules free to rotate, notably vapor \( \text{H}_2\text{O} \))
    - Magnetic (weak, nearly only \( \text{O}_2 \))
Issues

• Refractivity is a function of molecular density
  – proportional to pressure only because air \approx \text{ideal gas}
  – \( P/T \) is only approximately proportional to molecular density (cf: compressibility \( Z \))

• Refractivity may be a function of molecular density, but is not exactly a linear one

• \( \rightarrow \) Expressions based on \( P/T \) must necessarily be approximate

• Not only coefficients could be inaccurate:
  – Higher accuracy demands that the functional form is reconsidered
Back to basics:

• Refraction index: $n = \sqrt{\varepsilon_r \mu_r}$
  – Function of the electric and magnetic responses of the material

• In the atmosphere (sea level)
  – $\varepsilon_r \equiv 1 + \chi_e \approx 1.0006 - 1.0009$ (dry/moist)
  – $\mu_r \equiv 1 + \chi_m \approx 1.0000004$ (oxygen)

• Approximately:
  – Rough estimates: $N \equiv 10^6(n - 1) \approx \frac{1}{2} 10^6(\chi_e + \chi_m)$
  – Electric refractivity: $N_e \approx 300 - 450$
  – Magnetic refractivity: $N_m \approx 0.2$
Dielectric constant:

• Relationship between the dielectric and microscopic properties
  – Clausius-Mossotti, Onsager
  – Sum over all substances i
    \[
    \frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{1}{3\epsilon_0} \sum_i N_i \left( \alpha_i + \frac{\mu^2}{3k_B T} f(\epsilon) \right)
    \]

• Notice that
  – The relationship is a function of particle densities \( N_i \)
    ▪ Not partial pressures
  – The factors
    ▪ \( \frac{\epsilon_r + 2}{\epsilon_r} \) (enhancement of the response due to the polarizable environment)
    ▪ \( f(\epsilon) \) (modulation of polar response, very close to 1 for vapor)
    ▪ Sources of nonlinearity between refractivity and density

• Nonlinearities are weak, but not zero
  – Pressure vs density
  – Density vs dielectric constant
Relative permeability:

- Similar to dielectric, but simpler
  - Sum over all substances
- Function of particle densities \( N_i \)
  - But only oxygen is significant
- Permeability barely detectable, but non-negligible
- Nonlinearities are negligible

\[ \mu_r - 1 = \sum N_i B_i \]

Molecular magnetic susceptibility
Are resonances important?

- H₂O resonances ~23 GHz
- O₂ resonances ~50-60 GHz

- Very far from L1, L2: GPS is well in the static regime
  - We checked with Liebe’s MPM model

- But resonances are important to choose among available empirical measurements
  - Some published measures of polarizability are closer to the resonances (useless)
  - Yet others are also far but at the high frequency side
    • Static polarizability ≠ High freq polarizability! (not to 10⁻⁴)
Approximate contributions

- Figures are approximate only, for MSL conditions
- Dry components: Fractions are wrt dry
- Water contribution: representative of ~25°C moist air
- Other substances were verified, but all contribute less
- Refractivities in N-units

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mole fraction</th>
<th>Electronic Refr</th>
<th>Polar Refr</th>
<th>Magnetic Refr</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>0.780840</td>
<td>217.63</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>O2</td>
<td>0.209460</td>
<td>52.61</td>
<td>0.00</td>
<td>0.19</td>
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<tr>
<td>Ar</td>
<td>0.009340</td>
<td>2.46</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CO2</td>
<td>0.000383</td>
<td>0.18</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ne</td>
<td>0.000018</td>
<td>0.001</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>H2O</td>
<td>0.03</td>
<td>6.92</td>
<td>128.99</td>
<td>0</td>
</tr>
</tbody>
</table>
Critical elements

• We next examine how critical is to know each parameter involved
  – Parameters of dry air (mole fractions, molecular properties)
  – Parameters of water

• The case of dry air is very different from water vapor
  – An NWP system assumes dry air is relatively well understood
    • T, P are smooth, well behaved
  – An NWP system assumes much less about water vapor
    • Amount and distribution are assumed very variable and poorly known

• NWP model must accommodate larger errors WV
  – There is more room to allow less accuracy in the physical properties of WV
Critical dependencies (dry air)

• Approximate values for dependencies in dry air
• Target: we want to describe the ~300 N units at sea level with 0.01% accuracy
• Allowed error: 0.03 N units
• Next are the fractional errors per parameter that we can tolerate

```
<table>
<thead>
<tr>
<th>Substance</th>
<th>Mole fraction %</th>
<th>Polarizability %</th>
<th>Susceptibility %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>0.01</td>
<td>0.01</td>
<td>100.00</td>
</tr>
<tr>
<td>O2</td>
<td>0.05</td>
<td>0.05</td>
<td>100.00</td>
</tr>
<tr>
<td>Ar</td>
<td>1.00</td>
<td>1.10</td>
<td>100.00</td>
</tr>
<tr>
<td>CO2</td>
<td>17.00</td>
<td>26.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Ne</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
```

• The only parameters that are challenging are the polarizabilities of N\textsubscript{2} and O\textsubscript{2}
• Interestingly, we do need to account for (easy but necessary)
  – Ar: We need 1% accuracy
  – CO\textsubscript{2} and the magnetic susceptibility of O\textsubscript{2}: we can tolerate 10% error
Critical dependencies (water vapor)

- Approximate values for dependencies in moist air
- Target: we want to describe the ~300-450 N units at sea level
- If we allow the same error: 0.03 N units
- Next are the fractional errors per parameter that we can tolerate

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mole fraction %</th>
<th>Polarizability %</th>
<th>Dipole %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O</td>
<td>0.02</td>
<td>0.40</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- The most challenging parameter is the water dipole (but is ok)
- We also need to account for (feasible, also)
  - Water polarizability: 0.4% accuracy

- Mole fraction of water is a critical element, but for the NWP system, **not for the expression of refractivity**
Towards an expression of \( N(T,P_d,P_w) \)

- The most critical term is \( k_1 \)
  - \( k_1 \) is not a constant
    - Compressibility
    - Dielectric enhancement
- Accurate expression is complex
- We are targeting the substitution of \( k_1, k_2, k_3 \) (\( k_1 \) is the most critical):

\[
N = f_1(T, P_d, P_w) \frac{P_d}{T} + k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2}
\]

- Figure illustrates the nonlinearity.
- We have a model for \( N(T,P_d,P_w) \)
  - Practical expression upcoming
And now some updates

- Recent performance of GPSRO at Environment Canada
EC analysis and forecast system

• GEM Global Environmental Multi-scale Model
  – Global grid 800x600 or ~ 33 km resolution
  – 80 vertical levels
  – Model Lid at 0.1 hPa (~ 65 km)

• 4D-Var Incremental data assimilation system

• Drives a regional systems
  – North America, ~ 15 km resolution
  – Focused high resolution LAMs
    ▪ Including Vancouver Olympics (nested 15, 2.5, 1 km)

• Data
  – Anchor data for upper air: Radiosondes, GPSRO
  – With dynamic bias correction:
    ▪ Radiances AMSU A&B, SSMI, AIRS, GOES
  – Also:
    ▪ Aircraft reports, surface stations, wind profilers
    ▪ Winds: scatterometers, atmospheric motion vectors
The 0.1 hPa-lid model

GPSRO vs low lid and high lid

- **GPSRO vs Meso Global** (k4h7cb21)
- **GPSRO vs Meso Strato** (k4h7cy9u)

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- **GPSRO** assimilated in Meso Global
- **Meso Strato** in Meso Global

- **BIAS**
- **STD**

**Mean & Std. dev. of (O−F)/F**

- **0.04 hPa**
- **1 hPa**
- **2 hPa**
- **5 hPa**
- **10 hPa**
- **20 hPa**
- **50 hPa**
- **100 hPa**
- **200 hPa**
- **500 hPa**
- **700 hPa**
- **900 hPa**

- **Mean & Std. dev. of (F−O) (in K)**

- **0**
- **−10**
- **−5**
- **0**
- **5**
- **10**

- **0.6 hPa**
- **1 hPa**
- **2 hPa**
- **5 hPa**
- **10 hPa**
- **20 hPa**
- **50 hPa**
- **100 hPa**
- **200 hPa**
- **500 hPa**
- **700 hPa**
- **900 hPa**

Page 23
Recent COSMIC modification I: The status before, (O-P)/P, (O-A)/A

- Let’s ignore low tropo & lid
  - Both are of lower quality
  - Focus on 10-30 km altitude

- COSMIC biased +

- METOP, GRACE, biased -
Recent COSMIC modification II: The switch

• Modification in the right direction, but slightly overshooted
• COSMIC vs METOP still biased (but now inversely)
  – Probably also wrt GRACE, but stats too noisy
Summary

• We have a preliminary new expression for $N(T,P,Pw)$
  – Reviews impact of compressibility
  – Collective enhancement of refractivity
  – Nonlinear in partial pressures ($k1$ is not a constant)
  – Details still in progress

• We recently (Jun 2009) increased the lid
  – Very good results
  – More benefit is extracted from GPSRO data

• We have monitored the recent modification in COSMIC
  – There was a bias in COSMIC vs (METOP & GRACE)
  – Modification has overshooted METOP & GRACE
Thank you!