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GPS radio occultation sounding to support General Circulation Models

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Summary. — An assessment of the suitability of the horizontal and vertical resolution of GPS radio occultation measurements for climate studies is carried out. Simple physical relations are used to estimate the consistency between horizontal and vertical resolutions of radio occultation measurements as compared with those of the existing observing systems. In particular, the horizontal scale of the upper troposphere water vapour is investigated by analysing the variability of the refractivity index using the re-analysis data from NCEP/NCAR. The computation shows that the 300 km horizontal resolution of GPS radio occultation is within the useful range and captures the water vapour variations that are relevant for climatological purposes. Next, focusing the analysis on the requirements of the vertical resolution, we study the sensitivity of a radiative model to changes in the vertical resolution, assessing the impacts of these variations on the atmospheric equilibrium. For this purpose one reference profile and other five with lower vertical resolutions are used to perform the experiment. Results show that the model is sensitive to variations in the vertical sampling, suggesting that high vertical resolution measurements are necessary for an accurate observation of the atmosphere. To further assess the influence of the vertical sampling, the thermal tropopause height dependence on the number of layers considered is studied. Results indicate that the highest vertical resolution is needed for determining the radiative component of the tropopause dynamics.

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PACS `92.60.Bh` – General circulation.
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1. – Introduction

Sounding the atmosphere by tracking the changes of refractivity impacting the propagation of radio signals from satellites of the Global Positioning System (GPS) to satellites

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in Low-Earth-Orbit (LEO) during the occultation phase represents the only practical way to observe global profiles of temperature, humidity and pressure with vertical resolution less than one kilometre as necessary to appreciate discontinuities such as the tropopause. A wide international effort has being deployed to implement suitable space systems based on constellations of LEO satellites equipped with appropriate GPS receivers.

It should be noted that there is no practical alternative to the radio occultation technique for providing global scale very high vertical resolution sounding. Obviously, the radiosonde network provides the necessary vertical resolution but is extremely sparse and irregular. Infrared satellite sounding, even when performed by spectrometers, provides vertical resolution degrading with increasing height from some 1 km in the lower troposphere to 2-3 km at tropopause level and worse above; in addition, availability and quality are affected by the presence of clouds. Microwave sounding is nearly cloud-free but the vertical resolution is worse by a factor around 2 in the troposphere (better performance in the stratosphere). Sub-kilometre vertical resolution could only be, in principle, achieved by dual-frequency lidar, but this type of instrument cannot provide significant horizontal coverage. Infrared and microwave sounding have the advantage of good horizontal resolution (some 10 km in infrared, 50 km in microwave), that is a problem for radio occultation (some 300 km). The other problem with radio occultation is the scarce number of events/orbit so that, for reasonably frequent global coverage, a constellation of several satellites is necessary (for example, 24 satellites for global sampling at 300 km intervals in 6 hours). Availability and distribution are regular, since it is a cloud-free technique.

An important feature of the radio occultation principle is that it provides "absolute" measurements (the basic observation is time, or phase). This is extremely interesting for long-term climate monitoring, both for detecting trends and to enable time-integrated measurements of accuracy impossible to be achieved or even approached by any instantaneous measurement. In Italy, an activity named ASTRO (Atmospheric Sounding Through Radio Occultation) has been running since 1998, representing a joint effort of several scientific institutes and one industry. The objective of ASTRO is to promote the implementation of a constellation large enough as to meet user requirements stemming not only from climate application, but also from operational meteorology, as well as from ionosphere study as a matter of opportunity. This long-term objective passes through intermediate steps such as single-flight opportunities and small-size constellations applicable to climate.

The first initiative in the ASTRO framework was to submit a proposal in response to the European Space Agency (ESA) Call for Outline Mission Proposals for Earth Watch Partnership, in February 1998 (proposal leader: the LABEN Company). As a follow-on, ESA delivered a contract for the study of an Atmospheric Profiling Earth Watch (APEW; study leader: Matra Marconi Space, with LABEN), run in 1999-2000. The ASTRO study funded by the Agenzia Spaziale Italiana (ASI) was run in 2000-2002 (study leader: University of Rome, Department of Physics). Meanwhile, ASI delivered a contract to LABEN intended to develop a prototype radio-occultation sounding payload. The industrial development driven by ASTRO requirements is characterised by the attempt to improve as much as possible the applicability of the measurement to the lower troposphere (a problem for this limb-sounding technique). The payload is designed to be superior to other similar instruments currently used or being developed, in terms of providing useful measurements down to surface in most atmospheric conditions. This industrial development incorporates a science programme which is being implemented by five scientific institutes of Universities and the Consiglio Nazionale delle Ricerche (CNR).

The ASTRO activities includes:

i) analysis of user requirements in the fields of operational meteorology, climate monitoring and ionosphere study;

ii) development of constellation concepts sized for meeting the requirements from the various applications;

iii) studies of a payload suited to meet the most stringent user requirements;

iv) search of flight opportunities for the defined payload;

v) atmospheric modelling for on-board software implementation and experimental characterisation of the performances of radio occultation sounding (Polytechnic of Turin);

vi) demonstration of the benefit of radio-occultation sounding in the following applications:

– upper troposphere water vapour and tropopause study (University of Rome),

– reconstructing the Mediterranean hydrological cycle (University of Camerino),

– impact on Numerical Weather Prediction models (CNR Istituto di Scienze dell'Atmosfera e del Clima, Bologna),

– investigating the topside ionosphere (CNR Istituto di Fisica Applicata "Carrara", Florence).

This paper deals with one aspect considered in the framework of the research activity of the University of Rome: the suitability of the spatial resolution of radio occultation sounding for the purpose of initialising General Circulation Models (GCM). To ensure success to the radio occultation enterprise, it is necessary to demonstrate on the one hand that the coarse horizontal resolution (about 300 km, the major limitation of the radio occultation technique) is anyway sufficient to the purpose; on the other hand, that the high vertical resolution (less than 1 km in the upper troposphere/lower stratosphere) is effectively beneficial.

The paper is organised as follows. The issue of horizontal resolution is examined in sect. **2** by evaluating the spatial atmospheric variability of the refractivity index. A physical relationship between horizontal and vertical resolutions for meteorological variables is presented and it is compared with those of the existing observing systems. In sect. **3**, the horizontal scale of the upper troposphere water vapour is investigated. Re-analysis data from the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) are used to compute the refractivity index during the period 1991-2000 in the area 90°W-90°E, 20°N-90°N. As a measure of the typical horizontal scale of refractivity index variability, a spatial correlation function is used.

Next, in sect. **4**, focus is placed on the requirements posed on the vertical resolution and their impact on the radiative property of the atmosphere. The radiative model used to perform the sensitivity is "Streamer" [1]. Six atmospheric profiles with different vertical resolutions are considered. Then, a water vapour perturbation is applied to the atmospheric profiles and the radiative response to this change is computed.

To further assess the influence of the vertical sampling, the thermal tropopause height dependence on the number of layers considered is studied and the main results are described in sect. **5**. Conclusions are drawn in the final section.

2. – Consistency between horizontal and vertical resolution

Let us consider a theoretical relationship between horizontal and vertical resolution for meteorological variables and let us evaluate if the resolution of radio occultation measurements are physically consistent with this relationship.

TABLE I. – *Vertical resolution* Δz *as a function of* $\Delta\phi$ *for different latitudes.*

$\Delta\phi$ (deg)	Δz (km) $\phi = 0°$	Δz (km) $\phi = 60°$	Δz (km) $\phi = 45°$	Δz (km) $\phi = 22.5°$
1	1.4×10^{-2}	0.34	0.39	0.28
2	5.6×10^{-2}	0.68	0.78	0.55
4	2.24×10^{-2}	1.35	1.55	1.10
8	0.896	2.7	3.10	2.19

Lindzen and Fox-Rabinovitz [2] showed that, in the quasi-geostrophic approximation, the horizontal resolution $\Delta\phi$ (with ϕ the latitude) and the vertical one Δz are related as

$$\Delta z = \frac{\Omega a \sin(2\phi)}{N_S}(\Delta\phi)\,. \tag{1}$$

In tropical regions we have, instead

$$\Delta z = \frac{2\Omega a}{N_S}(\Delta\phi)^2\,, \tag{2}$$

where $a = 6371$ km is the Earth's radius, $\Omega = 2\pi/86400\ \text{s}^{-1}$ is the rotation rate of the Earth and $N_S = 3\pi/300\ \text{s}^{-1}$ is the Brunt-Väisälä frequency. The values of Δz as a function of $\Delta\phi$ for different latitudes are shown in table I. As is known, the rawinsondes have a vertical resolution within the range 0.5–1 km and a horizontal resolution that depends on the world region (in Europe, North America and Eastern Asia, the rawinsondes data are available every 2-3 degrees, but in the rest of the globe the horizontal distribution of measurements is coarser or, sometimes, very sparse). Satellite instruments, instead, can provide higher horizontal resolution with measurements every 0.3–1 degrees, but vertical resolution about 1.5 km. The radio occultation measurements have a horizontal resolution between 2 and 3 degrees, while the vertical one is reduced to about 500 m (far from the Earth surface).

In fig. 1 (figure modified from [2]) these resolutions are compared with the theoretical ones. It can be argued that rawinsondes can provide consistent resolution only in regions where launches are denser, while satellites have a vertical resolution not enough accurate when compared with the horizontal one. On the other hand, the radio occultation measurements fit the requirements of the theoretical relationship in mid-latitudes and in polar zones. For tropical and equatorial regions, the resolution remains too coarse.

This result suggests that the horizontal resolution of the radio occultation data is sufficiently accurate for the atmospheric observation at mid latitudes and that horizontal and vertical resolutions are consistent. Thus, GPS data, integrated with the ones coming from other observing systems, can provide correct initial conditions for Numerical Weather Prediction (NWP) models and GCMs.

3. – Horizontal scale of the refractivity field

We perform some experiments to evaluate the horizontal scale of variability of temperature and water vapour fields to assess if radio occultation data can characterize the

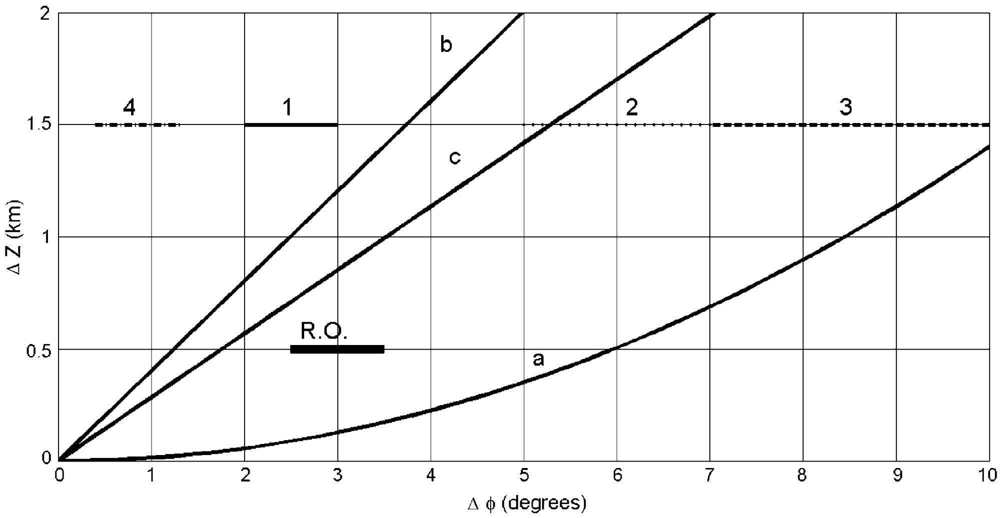

Fig. 1. – Horizontal and vertical resolution for rawinsondes (R), satellites (S) and radio occultation data (R.O.). Line 1 refers to R for United States, Europe and Eastern Asia; dotted line 2 refers to R for Africa, South America, Siberia and Canada; dashed line 3 refers to R for the rest of the globe; dash-dotted line 4 refers to S. The bold line refers to R.O. measurements. The line labelled with "a" refers to theoretical consistence for horizontal and vertical resolution at the Equator; line "b" the same but for 45 degree latitude, and line "c" for 22 degree latitude.

main features of these atmospheric variables.

We use temperature and specific humidity data from the NCEP/NCAR reanalysis database. Data are provided with a horizontal resolution of 2.5 degrees in longitude and latitude for 8 pressure levels, namely 1000 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa and 300 hPa. We consider the area between 90°W-90°E and 20°N-90°N (that includes the Mediterranean basin, Europe, part of Asia and North Africa) and we select the daily means of variables for 10 different winters (December, January and February: DJF), starting from 1991 till 2000.

Following Bevis *et al.* [3] we compute the refractivity N as

$$N = \underbrace{77.6\frac{P}{T}}_{NT} + \underbrace{3.73 \cdot 10^5 \frac{e}{T^2}}_{NV}, \tag{3}$$

where P is the atmospheric pressure, T is the temperature and e is the water vapour partial pressure. According to Zou *et al.* [4], we consider separately the dry contribution of the refractivity NT, and the wet one, NV. To evaluate the horizontal scale of these two components, we compute their decorrelation length. For each vertical level we transform the bi-dimensional fields of N, NT and NV in a one-dimensional sequence, computing the mean values for points that have similar distance. For example, considering as the first value of the series the point in the South-West corner of the map, the second value of the series is computed averaging the points that are 2.5 degrees away from the first; the third value is given by the mean of the points that are 5 degrees away from the first, and so on. The correlation function of the series obtained is computed and then the

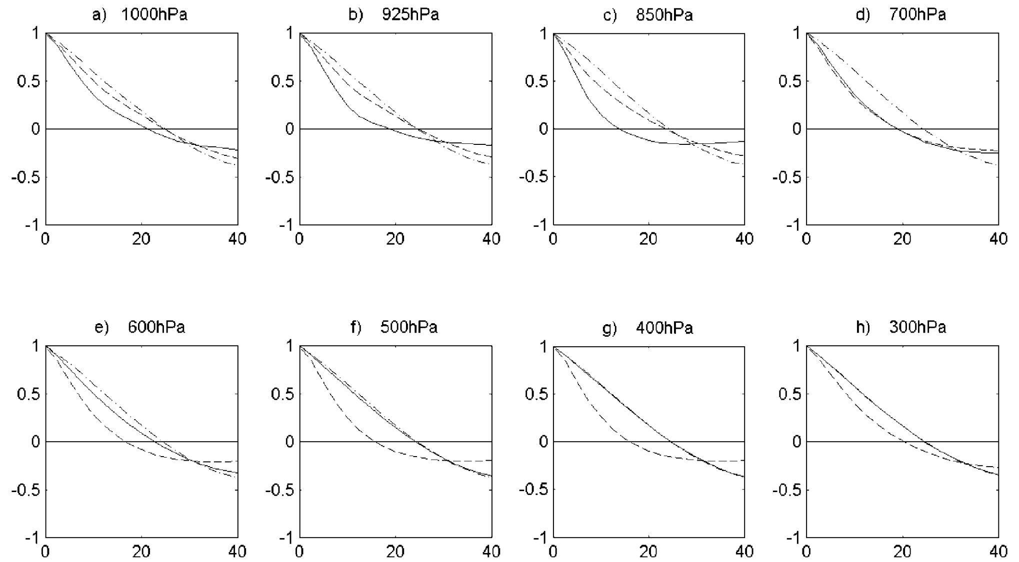

Fig. 2. – SCF for N (solid line), for NT (dot-dashed line) and for NV (dashed line) at 8 different levels. x-axis is the decorrelation length in degrees.

decorrelation length is evaluated (hereafter denoted with Spatial Correlation Function, SCF).

Let D be the distance when SCF is equal to zero. We wish to show that, for N, NT and NV, the distance D is large enough to accept 300 km (*i.e.* the horizontal resolution of GPS radio occultation measurements), as a suitable horizontal resolution for atmospheric sounding.

The winter monthly means of the SCFs are shown in fig. 2 for N, NT and NV at the 8 pressure levels considered. The SCFs for NT (dot-dashed lines) show a decorrelation length equal to 25 degrees for all the levels. This is because the vertical structure of temperature is independent of the horizontal variation of the field on this scale, but it appears to be related to convective motions and the radiative transfer. This statement is confirmed also by other climatological observations. The decorrelation length of 25 degrees corresponds to different values in kilometres depending on the latitude: at low latitudes (about 20 degrees) it is $\sim$ 6000 km, at mid-latitudes $\sim$ 5000 km and in polar regions $\sim$ 1000 km. This result highlights that the temperature field has a horizontal variability larger than the horizontal resolution of GPS radio occultation measurements.

In fig. 2 we show how N and NV SCFs vary at each level. For levels between 1000 and 850 hPa (fig. 2a, 2b, 2c), NV (dashed line) has a decorrelation length comparable with NT; N (solid line) at 1000 hPa and 925 hPa has a decorrelation length between 18 and 20 degrees ($\sim$ 4500 km at 20°N; $\sim$ 3500 km at 45°N; $\sim$ 845 km at 80°N). For the level at 850 hPa the decorrelation length is shorter, but more than 12 degrees. At 700 hPa the SCF signals for N and NV are similar, whereas there is a higher decorrelation length for NT. At this pressure level, the horizontal structure of the total refractivity N is mainly influenced by the wet part, because the water vapour amount is high enough to influence the structure of N and NV that have a decorrelation length lower than NT.

Analysing the middle troposphere (600 hPa and 500 hPa), the SCF of N is close to that one for NT because the water vapour is less concentrated in that region. NV has a decorrelation length shorter ($\sim 15°$) than N and NT. The lower quantity of water vapour in this part of the atmosphere leads to a minor weight of the wet component in N. At these pressure levels, in fact, the water vapour has a lower concentration compared to the surface, but an elevated spatial variability remains. It is probably due to the convective activity often occurring in the tropical regions.

Considering higher levels (400 hPa and 300 hPa), NT and N have the same scale of variability, because the water vapour amount at these levels is negligible.

For levels between 1000 hPa and 700 hPa the variance of the N SCF (here not shown) has a decorrelation length between 5° and 8°, that corresponds to $1300 < D < 2000$ km at 20°; $970 < D < 1500$ km at 45° and $240 < D < 381$ km in polar regions. Regarding NV SCF variance in the upper troposphere, the decorrelation length is between 8° and 10°. This variance analysis suggests that for 68% of the cases the decorrelation length is higher than the GPS horizontal resolution.

In fig. 3 maps for N, NT and NV are shown for a particular day (1st January 1991) for 1000 hPa, 500 hPa and 300 hPa. Maps in fig. 3a, 3b, 3c refer to 1000 hPa. If we exclude the areas where particular features are present, like the maximum at (20°N, 40°E) in the NV map, the horizontal scale is coherent with the result previously shown.

Comparing the first map with the other two at 1000 hPa, it is possible to recognize the contribution of the two signals NT and NV. Between 20°N and 45°N the field is dominated by the wet part NV, whereas at higher latitudes, where the amount of the water vapour is lower, the signal is dominated by NT. It is possible to clearly identify two zones of relative maxima nearby the Hudson bay and the Artic sea.

At 500 hPa (fig. 3d, 3e, 3f), due to the small amount of water vapour, $N$is dominated mainly by the NT contribution.

Finally, in fig. 3g, 3h, 3i maps for the 300 hPa level are shown. Here the water vapour amount is extremely low (see fig. 3i) and N is dominated by the NT contribution.

These maps confirm the previous results: the features of the atmospheric refractivity $N$and of its two components NT and NV, have horizontal scales larger, or at least equal, than the horizontal resolution of the radio occultation data (300 km). This allows using the GPS measurements for GCM and mesoscale models initialisation. Obviously, the atmospheric variability that occurs on a shorter horizontal scale remains unsolved.

4. – Sensitivity of a radiative model to changes in the vertical resolution

In this section, we study the sensitivity of a radiative model to changes in the vertical resolution, assessing their impacts on the equilibrium state of the atmosphere. The hypothesis of different vertical resolutions is made also in order to simulate the measure of the atmospheric variables with instruments of different vertical resolution. In fact, by computing the differences at the radiative equilibrium, we can evaluate the advantage in using very detailed vertical profiles.

Let us consider one reference profile (89-levels) and other five (25, 27, 33, 43 and 63-levels) obtained from this one by decreasing the vertical resolution and linearly interpolating the data.

We consider a tropical atmosphere with a vertical resolution extremely accurate, especially in the troposphere, where the most important atmospheric phenomena take place; then, the impact of a water vapour perturbation on the radiative equilibrium, when different vertical resolutions are taken into account, is analysed.

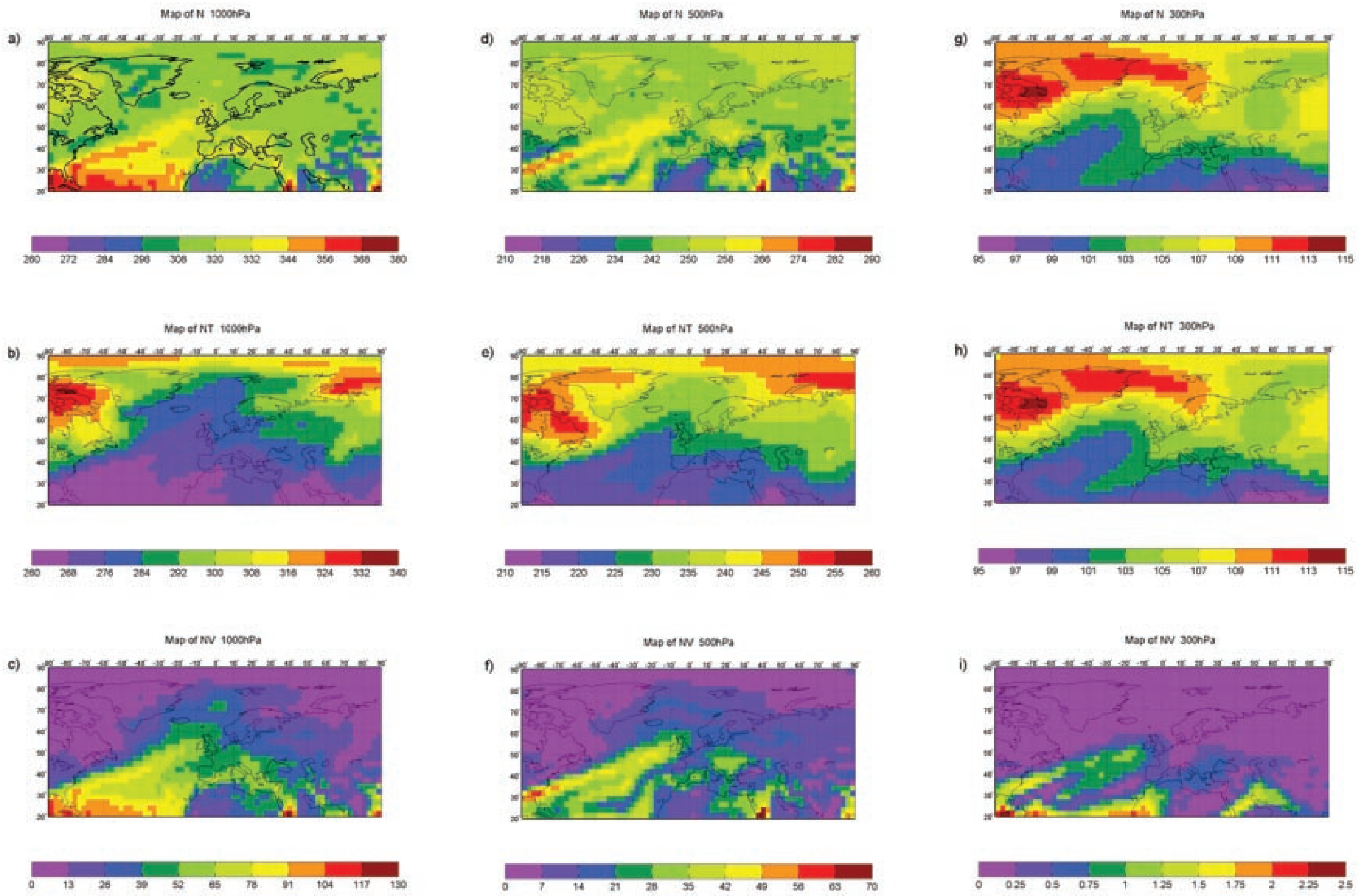

Fig. 3. – Maps of N, NT and NV for 1st January 1991 at 1000 hPa (a, b, c), 500 hPa (d, e, f) and 300 hPa (g, h, i).

We use the radiative model "Streamer" [1] for the sensitivity analysis. The model divides the electromagnetic spectrum into 129 bands. It allows a very accurate description of an atmospheric profile. For every pressure level it is possible to specify temperature, water vapour amount, aerosols type and concentration, cloud cover, particle size and shape and other parameters (see model description in [1]). The model computes cooling and heating rates.

If Φ is the net flux at an atmospheric layer, the heating rate τ is

$$\tau = \frac{\partial T}{\partial t} = \frac{g}{C_p}\frac{\partial \Phi}{\partial p}\,, \tag{4}$$

where T is temperature, t is time, p atmospheric pressure, C_p the specific heat at constant pressure, g the gravity acceleration and the ratio g/C_p is the well-known adiabatic lapse rate. With these variables it is possible to study the time evolution of the temperature profile neglecting dynamical interactions. In computing the temperature variation we consider only the radiative effects, adding the heating rate, obtained from the model, to the initial temperature profile, and iterating the process. The temperature T at time $t + \Delta t$ for the i-layer, is

$$T(t+\Delta t)_i = T(t)_i + \tau_i \Delta t\,. \tag{5}$$

Iterating the process, two states can be reached: a runaway, *i.e.* an increasingly warmer atmosphere, or a radiative equilibrium state, *i.e.* a state where the radiation absorbed by the atmosphere is re-emitted without any further heating or cooling. We compare the results obtained for the different vertical resolutions when the radiative equilibrium is reached.

The procedure applied to every atmospheric profile is: 1) compute the radiative fluxes for every layer; 2) compute the heating rates for every layer; 3) evaluate (5); 4) repeat the procedure until the equilibrium is reached, *i.e.* until, for every level i, the following relationship is satisfied:

$$|T(t+\Delta t)_i - T(t)_i| \leqslant \delta\,, \tag{6}$$

where $\delta = 0.005$ K.

For the radiative equilibrium we consider the fluxes at TOA (Top Of Atmosphere). Four experiments have been carried out, as follows.

4·1. *Experiment 1.* – In the first experiment a standard tropical atmosphere is considered with a vertical resolution of 250 m in the troposphere, degrading up to 20 km till the TOA. This atmosphere, that has the higher vertical resolution (89 levels), will be the reference one for our experiments. For this profile the radiative equilibrium is reached after 244 days, with a net flux at TOA of 268.54 W/m^2.

Figure 4 shows the six different vertical resolutions. The profiles differ for the number of levels and also for the vertical distribution of the layers. The profiles with 25 and 63 levels are very dense in the troposphere, whereas the ones with 27, 33 and 43 levels are less dense in the troposphere, while the vertical resolution is constant in z.

For all the atmospheres we consider the values after 244 days, *i.e.* the time needed to the reference atmosphere to reach the equilibrium.

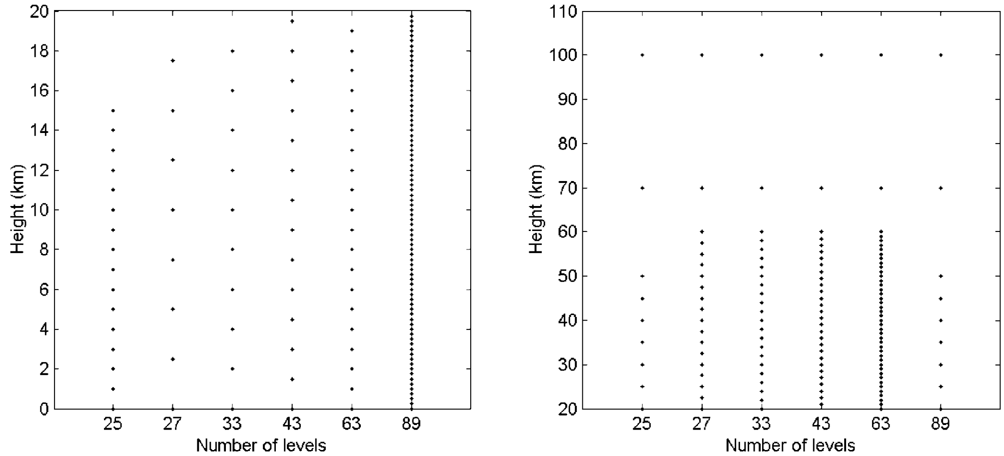

Fig. 4. – Vertical distribution of the levels for the six atmospheres used for the experiments.

As the flux variation due to doubling CO_2 in the atmosphere gives a difference of about 4 W/m^2 [5], we choose this value as a threshold for our experiments (values greater than the threshold means that higher vertical resolution is needed).

Table II shows the differences between the radiative fluxes at TOA for the five profiles and the reference one. For this experiment, the results suggest that the differences are not so large and less than the threshold. Thus, we may conclude that there is no remarkable impact of different vertical resolutions on the radiative equilibrium.

4·2. *Experiment 2.* – In the second experiment we introduce a perturbation on the water vapour profile: at 2 km we set water vapour content 10% higher than normal, and between 2 and 3 km the water vapour is reduced by 22%. The new water vapour profile has a different vertical distribution, but the same integrated value along the atmospheric column. For the five profiles we assign the value of the water vapour content for a level as the value of the corresponding level in the reference profile.

In table II the results for the flux differences at TOA are shown. The fluxes differences are larger than the ones of the previous experiment, but do not exceed 4 W/m^2.

However, some remarks can be outlined: profiles with higher number of levels in the troposphere (25 and 63) give a higher variation than the other ones because they are more

Table II. – *Flux differences at TOA between the reference atmosphere and each of the five profiles at the radiative equilibrium for the four experiments.*

	25 levels	27 levels	33 levels	43 levels	63 levels
Experiment 1	−1.69 W/m^2	−2.65 W/m^2	−0.12 W/m^2	0.83 W/m^2	−1.7 W/m^2
Experiment 2	3.33 W/m^2	−2.02 W/m^2	1.85 W/m^2	−0.49 W/m^2	3.32 W/m^2
Experiment 3	−4.31 W/m^2	−5.64 W/m^2	−3.70 W/m^2	−4.38 W/m^2	−4.33 W/m^2
Experiment 4	−1.68 W/m^2	−3.63 W/m^2	−0.31 W/m^2	0.90 W/m^2	−1.7 W/m^2

sensitive to the variation of water vapour. It seems that they respond in similar way. Thus, we may conclude that it is very important to have a detailed vertical resolution because the response of the model is sensible to the perturbations in the troposphere.

The other profiles, with less vertical resolution between 1 and 3 km, give results closer to that for the reference profile because the integrated water content has been maintained constant.

4˙3. *Experiment 3*. – In this experiment we wish to simulate measurements made with some passive instruments. We use the same water vapour perturbation of the previous one. For each level in the five atmospheric profiles, the water vapour content is fixed as the mean of the water vapour content present in the same layer of the reference profile. For example, the atmosphere with 25 levels has a vertical resolution of 1 km in the troposphere. The value of the water vapour amount between 2 and 3 km is now given by the mean of the water vapour content over the levels included between 2 and 3 km in the reference atmosphere. This approach gives an over-estimate of the vertical distribution of the water vapour content and, differently than in the previous experiment, the columnar amount is not conserved.

The flux differences at TOA (see table II) are less than 6 W/m^2 and the atmospheres with 25 and 63 levels give similar results because the water vapour is mostly concentrated in the troposphere. This last feature is present in all the experiments and it is due to the fact that these two atmospheres have similar vertical sample in the troposphere, but different in the stratosphere. On the other hand, the 27 levels atmosphere differs more than the other ones because it has a coarsest vertical resolution in the lower troposphere and it is not able to describe correctly the water vapour perturbation.

4˙4. *Experiment 4*. – In this experiment the water vapour perturbation is considered in the same way of the second experiment, but now it is applied between 6 and 8 km. The differences obtained are about 4 W/m^2. Referring to experiment 2, we can see some differences due to the different height and magnitude (related to the less water vapour content in the upper levels) of the perturbation. Furthermore, this perturbation changes the emission levels for the water vapour, affecting the response of the model and sometimes the sign of the results.

4˙5. *Discussion*. – The experiments above show the importance of the vertical resolution in climate study. Different results are obtained, in fact, by using different vertical resolutions for the same atmospheric profile. This suggests the importance to have measurements with high vertical resolution to properly detect possible perturbations occurring on the system, as in the case of the second experiment, where only a very good vertical resolution may measure the impact of the variation on the TOA flux. Experiment 4 shows that also the altitude where the measurements are provided is important. In fact, a good profile should be more detailed especially in the troposphere, where water vapour mostly varies. Profiles with 25 and 63 levels, in fact, that are more accurate in the troposphere, are more sensitive to water vapour perturbation than other ones. Thus, the contribution of radio occultation to the study of atmospheric processes is very important because avoids the limits of passive instruments, giving an accurate and consistent characterization of the atmosphere.

TABLE III. – *Tropopause heights in kilometres for six different profiles for the four experiments.*

	25 levels	27 levels	33 levels	43 levels	63 levels	89 levels
Experiment 1	13.0 km	15.0 km	14.0 km	13.5 km	13.0 km	12.75 km
Experiment 2	13.0 km	15.0 km	14.0 km	13.5 km	13.0 km	12.75 km
Experiment 3	14.0 km	17.5 km	16.0 km	15.0 km	14.0 km	12.75 km
Experiment 4	13.0 km	15.0 km	14.0 km	13.5 km	13.0 km	12.75 km

5. – Tropopause detection

The radio occultation technique allows to measure another very important feature in the vertical structure of the atmosphere: the tropopause height.

During the last two decades, the exchange of mass, water, and chemical constituents between the upper troposphere and the lower stratosphere has received increased attention. This exchange takes place across the tropopause, which is often marked by an abrupt change of the temperature lapse rate from the turbulently-mixed troposphere where temperature decreases with height, to the stable-stratified stratosphere, with temperatures constant or increasing with height. Studies of observations also suggest that the tropopause often marks the location of an abrupt transition in the values of atmospheric properties (*e.g.*, potential vorticity) and in the concentration of chemical species such as ozone, sulphur dioxide, and various nitrogen oxides [6]. These abrupt changes suggest that the tropopause is a thin layer separating the stratosphere from the troposphere. Accurate knowledge of the temporal and spatial structure of this transition zone is necessary to evaluate the exchange of mass, water, and chemical constituents between the troposphere and the stratosphere and also for climatic study.

To analyse the sensitivity to the measurements of the tropopause height on the vertical resolution, we consider the same atmospheric profile described above. We analyse the change of the tropopause height when the radiative equilibrium is reached.

At the initial state, the tropopause height is at 15 km and the tropopause temperature is 203 K for every profile, with the exception of the 33-levels profile that does not have any level at 15 km and the tropopause height is at 14 km.

For the reference profile, at the equilibrium state, the tropopause temperature decreases by about 8 K and the height decreases to 12.75 km. This effect, clearly documented in the literature ([7] and [8]), is related to an increasing of the lapse rate at the radiative equilibrium (10 K/km) with respect to the radiative-convective one (6.5 K/km), that is very close to the observed one.

Here we perform experiments considering the same atmospheric perturbation presented in the previous section. The results are reported in table III.

It must be noted that the experiments provide similar values of the tropopause height with the exception of the third one. In fact, in this case the tropopause height is raised. This effect is due to the presence of a grater quantity of water vapour in the troposphere that heats the column and, consequently, produces a raising of the tropopause height. From table III we can argue that the different vertical resolutions in the six profiles influence the tropopause detection and, sometimes, the value of tropopause height differs of 3 or 5 km from the reference atmosphere (atmospheres with 27 and 33 levels).

The same happens for the tropopause temperature: the values are almost the same (here not shown) for all experiments except for the third one, where the atmosphere with a poor resolution in the troposphere leads to values of the tropopause temperature lower than that for the reference atmosphere.

6. – Conclusions

In this paper we evaluated the suitability of different horizontal and vertical resolutions of the atmospheric measurements to assess whether the radio occultation technique may provide adequate resolution for climate study. We performed some experiments to analyse the spatial scale of refractivity, to test the response of a radiative model to variations on the vertical resolution and to assess the influence of the vertical sampling on tropopause height detection.

The results suggest that:

a) the relationship between vertical and horizontal resolution for atmospheric measurement shows that it is necessary to improve the vertical resolution of the atmospheric models and of the observing systems. The radio occultation technique can provide measurements with accurate vertical and consistent horizontal resolution.

b) The horizontal resolution of GPS measurements is accurate enough compared with the horizontal scale of the atmospheric refractivity.

c) The vertical structure of the atmosphere is very important, and the actual models are sensitive to variations in the vertical sampling. Results obtained with the radiative model show a good response of fluxes at TOA to changes in the vertical resolution. This means that measurements with a high vertical resolution have sizeable impact on models and they are necessary for an accurate observation of the atmosphere.

d) In all the experiments the atmosphere with higher vertical resolution (89 levels) provides more accurate results. Thus, the high vertical resolution of the radio occultation measurements can improve the parameterisation of the radiative processes in the atmosphere, the weather prediction and the climate analysis.

e) The tropopause detection is sensitive to the vertical resolution of measurements and radio occultation data can improve the observation and the analysis of the tropopause height and temperature.

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REFERENCES

[1] Key J. and Schweiger A. J., *Comput. Geosci.*, **24** (1998) 443.
[2] Lindzen R. S. and Fox-Rabinovitz M., *Mon. Weather Rev.*, **117** (1989) 2575.
[3] Bevis M., Businger S., Herring T. A., Rocken C., Anthes R. A. and Ware R. H., *J. Geophys. Res.*, **97** (1992) 15787.
[4] Zou X., Kuo Y.-H. and Guo Y.-R., *Mon. Weather Rev.*, **123** (1995) 2229.
[5] Lindzen R. S., *Bull. Am. Meteorol. Soc.*, **71** (1990) 288.
[6] WMO, *Atmospheric ozone 1985: Global ozone research and monitoring report*, Rep. **16**, edited by World Meteorological Organization (Geneva, Switzerland) 1986.
[7] Manabe S. and Strickler R. F., *J. Atmos. Sci.*, **21** (1964) 361.
[8] Manabe S. and Wetherald R. T., *J. Atmos. Sci.*, **24** (1967) 241.