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Requirements Definition for Future DIAL instruments

Technical Note 110 (TN110):

Analysis and Definition of Observation Requirements for Pressure and Temperature Measurements to be used In Numerical Weather Prediction (NWP)

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Summary

This document recapitulates the nature of current schemes for numerical weather prediction (NWP). The data assimilation schemes, which provide consistent and quality checked initial values for every model forecast, receive large data streams from conventional networks and passive satellite sensors. Nevertheless global NWP with a forecast range up to two weeks ahead still has a great demand for additional high quality data of the basic parameters pressure and temperature. Even today extended regions exist over the world oceans, especially in the southern hemisphere, where surface pressure and well known located temperature and geopotential height data are lacking.

Active remote sensing with dual wavelength laser techniques (DIAL) from space appears to be attractive because of the more accurate height allocation compared to passive techniques. Tables of the necessary accuracies and spatial resolutions for global NWP applications are given together with recommendations for spatial coverage. Observational requirements for *global* NWP are presented for four vertical layers concerning temperature and pressure; these are seen to be implicitly valid also for climate analysis and regional NWP.

Finally the findings for surface pressure are cross-checked with the data assimilation practice at ECMWF as of the end of 2004.

Numerical weather prediction: A century of development

It is useful to note that all current weather forecasts or, perhaps better phrased, pre-calculations of future atmospheric states are based on a concept initially introduced exactly one century ago (Bjerknes, 1904). Exner (1908) was the first to present calculated pressure changes over the north-American continent, from an approximated version of the basic equations and 13 years after the event. Better known is the concept of a full primitive equation model put forward by Richardson (1922), together with a failed test application over Europe and the dream of a forecast factory staffed with human calculators. Exactly fifty years have passed since a Swedish group was among the first who experimented with the usage of electronic computers for quasi-operational numerical weather prediction (NWP; cf. Staff members, 1954).

Meanwhile global NWP is in daily operational use and has reached a remarkable quality level for 5 to 7 days ahead. To provide a background to understand the still existing necessity of reliable and well distributed initial data of pressure and temperature we give here a simple description of the nature of NWP (following Woods, 2003) followed by a short description of the networks used in currently in NWP.

<u>The weather is governed by physical laws</u>

The behaviour of the atmosphere is governed by a set of physical laws, as the conservation of mass, momentum, angular momentum and energy, which can be expressed as prognostic equations. These describe how atmospheric quantities or fields (such as pressure, temperature, wind speed and direction or humidity) will change from their values at the present time. A solution of these equations provides a description of the future state of the atmosphere – a forecast – derived from a current state (initial values), which then can be interpreted in terms of "weather", *i.e.* sunshine, cloudiness, rain and wind.

<u>Computers are regularly used to calculate changes to the atmosphere</u>

However, these equations are complex (they are *non-linear partial differential equations*). There is no exact solution that can provide the future values. Instead, numerical modelling techniques are employed to provide approximate solutions. In such algorithms, loosely termed *numerical models*, the fields are represented by a finite set of numbers, defined at, say, intersections of a computational grid. By using suited approximate forms of the equations, the future values of the numbers can be calculated with a computer. Representing fields with approximate numerical values is called *discretization* which emphasises the limits of the numerical approach. The smaller the set of numbers the coarser the discretization and the less detail is available about the future state of the atmosphere. On the other hand, the finer the discretization, the larger the amount of numbers to be dealt with, and the more demanding in terms of computer time the solution becomes.

Modelling for a limited area for short-range forecasting

The task can be made more manageable if not the whole atmosphere is treated but only a certain area or region, for example a part of Europe. This is called a *Limited Area Model*. Such models can produce a very detailed forecast, but they are useful only in the range several hours to about two days into the future – what is happening outside the treated area influences the weather inside it, the more so the longer the forecast interval in which one is interested.

Medium-range forecasting on the global scale

In Europe *global* NWP models are operated at the national meteorological services of France (Météo France), Germany (Deutscher Wetterdienst, DWD), the United Kingdom (Met Office) and at the European Centre for Medium-range Weather forecasts (ECMWF). ECMWF, for instance, predicts the behaviour of the atmosphere in the medium-range up to ten days ahead. In this time the future state of the atmosphere at any point can be influenced by phenomena at very distant geographical locations. Therefore the whole atmosphere must be included in the model – a model for medium-range forecasting must be global and must describe the atmosphere from the earth's surface to a height of 65 km. The discretization which can be afforded depends on the power of the computer that is available and how efficiently this power is used.

Making the forecast

In order to start the computer model, *initial* or starting conditions are required. Observations are used to determine the state of the atmosphere at each point throughout the model domain. The forecast is made in short steps, of about 15 minutes ahead, with each forecast providing initial conditions for the next forecast step. The preparation of initial conditions is both a delicate and demanding task which in the ECMWF forecasting system requires almost as much computer resources as a ten day forecast.

Initial conditions for the ECMWF global model are prepared by making an appropriate synthesis of observed values of atmospheric fields taken over a 24 hour period and short-range forecasts provided by the global model itself. This synthesis is called *data assimilation*, for which the use of both observations and model forecasts is required. High quality data are sparsely and irregularly distributed over the globe. Short-range model forecasts carry forward in time knowledge of earlier observations and also provide a crucial background for extracting useful information from satellite observations using passive sensors.

Current NWP exemplified by the ECMWF modelling system

At present ECMWF discretizes the atmosphere vertically with 60 levels between the ground and a height of 70 km and horizontally with 511 triangularly truncated spherical waves. Transposed to a linearly reduced Gaussian grid this results in 20,911,680 atmospheric grid points plus 1,394,112 at the surface and various soil layers below. The average horizontal grid spacing is close to 40 km, which makes it possible to resolve features of a horizontal extent down to 80 km.

As regular input of atmospheric data is more 200,000 pieces are typically taken per 6h interval. The comprise as their backbone conventional in-situ observations of the categories SYNOP, TEMP, PILOT (all over sea and land), drifting buoys (over the oceans) and aircraft reports. Synthetic data (PAOB) are important over data void regions of the oceans. An increasing amount of information stems from a diverse variety of (passive) satellite data after suitable retrieval procedures (categories: SATOB, TOVS/ATOVS, SCAT surface winds, SSM/I total water vapour, WV radiances, MODIS winds, AIRS, AMSU-A, AMSU-B). Further details are given below in section *data assimilation*.

Pressure and Temperature in NWP

The basic variables, which determine the large scale motions of the atmosphere are the three-dimensional fields of pressure (or geopotential height of surfaces of constant pressure), temperature, horizontal wind and direction (or the zonal and meridional wind components) and humidity, as was already outlined by Bjerknes (1904). Active remote sensing missions using satellite-borne lasers are underway for one (line-of-sight) wind component (ESA explorer core mission ADM-Aeolus; Reitebuch et al. 2003, ESA 2004a), and they are in the selection process for humidity (proposal for future ESA explorer core mission WALES; ESA 2004b). Therefore it is consistent to outline in this document requirements for possible future missions to retrieve pressure and temperature from space with active remote sensing techniques. Their technical feasibility is dealt with in accompanying documents.

The earth's surface represents the lower boundary of the atmosphere, which is modelled at ECMWF as a stack of 60 layers. Surface pressure equals the gravitational force (weight), which is exerted by the entire column of air above an unit area. It is closely linked to the geopotential height of the 1000 hPa pressure surface.

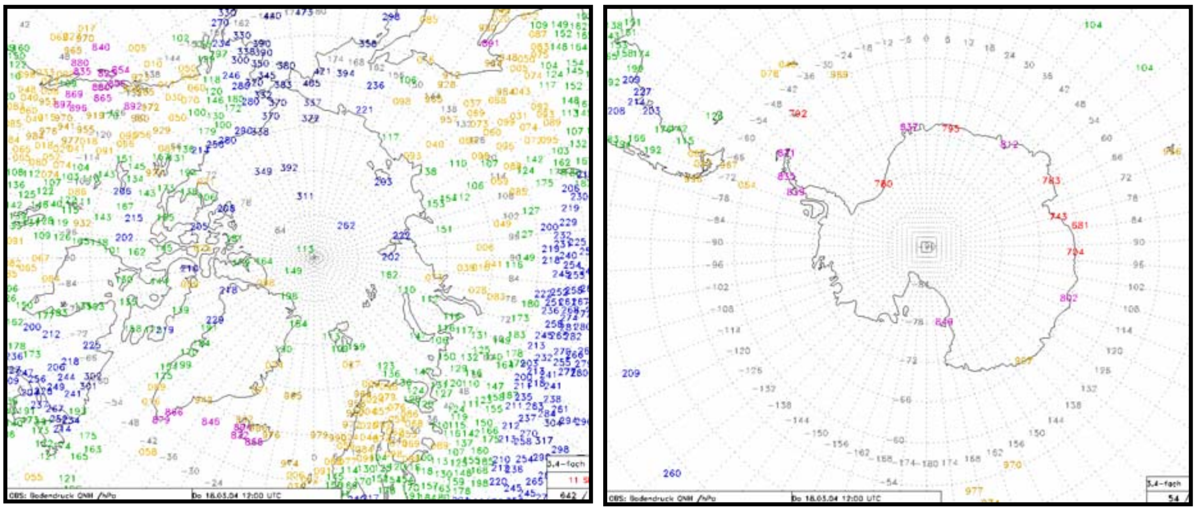


Figure 1: Surface pressure observations for 18 March 2004, 12 UT around the North Pole (642 plotted of 1854 altogether; left) and around the South Pole (54 plotted of 89 altogether; right) as used for the initialisation for the Global-Modell of DWD.

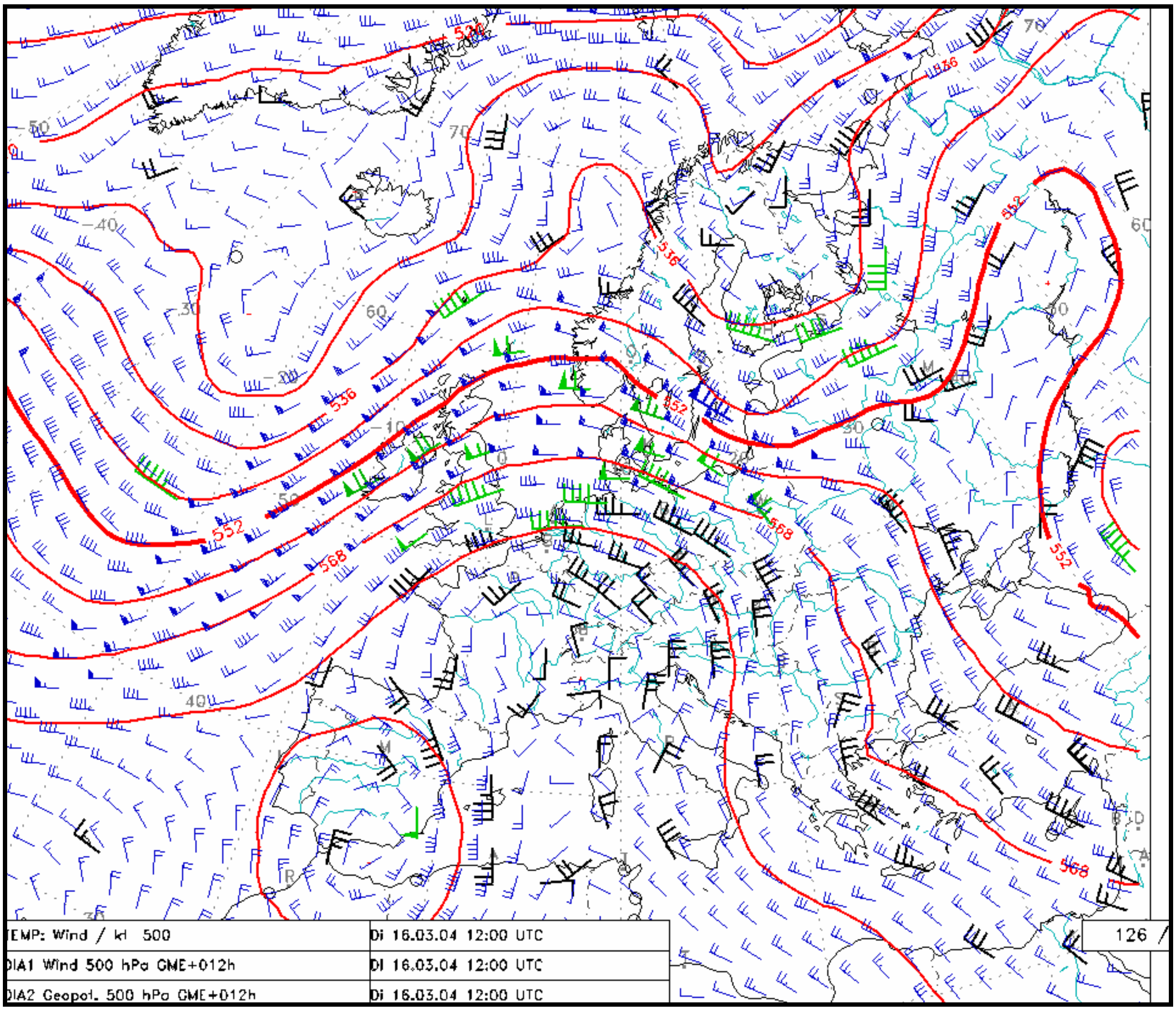


Figure 2: State of the atmosphere in about 5.5 km height (500 hPa pressure level) above Europe and parts of the North Atlantic on 16 March 2004, 12 UT, reveling the close link between flow and pressure height: 12 hourly forecast of the geopotential height (isolines in dam) and of horizontal wind (equally spaced barbed flags indicating the direction and speed; triagles: 50 kn; long / short dashes: 10 / 5 kn; from Global Modell of DWD) superimposed by 126 larger wind speed flags as measured by radiosondes (same convention).

At the sea surface a height difference of 8 m is equivalent to a pressure difference of 1 hPa. A correct initial description of the weather relevant high and low pressure regions (Highs and Lows) requires sufficiently densely spaced pressure observations. Figure 1 exemplifies for equally large areas around both poles that about 20 times more surface pressure observations are typically available for the north polar domain. Furthermore the large inhomogeneity in coverage between land and ocean areas becomes evident. Monthly figures for the average daily availability of surface pressure observations from synoptic stations (SYNOP) and drifting buoys (DRIBU) are regularly published for 5ºx5º boxes (ECMWF, 2004); during the whole of

February 2004 73 of the 648 larger 10ºx10º boxes did not contain a single pressure observation.

Above the ground, pressure is not measured at constant height surfaces, but the elevations of certain fixed pressure levels (e.g. 850, 700, 500, 400, 300, 200 hPa) are determined along the ascent of balloons carrying radiosondes. The horizontal gradient of this *geopotential height* of a certain pressure level yields a good approximation of the flow at that level (through the *geostrophic wind relation*). Figure 2 exemplifies this relation between the height gradient of the 500 hPa pressure surface and the corresponding flow from a 12 h forecast over Europe. The superimposed 126 wind measurements (determined from the lateral drift of the ascending balloons) show the coverage of radiosonde stations over Europe and the quality of the short-range forecast. But they also give an impression of the data sparse regions over the Atlantic or towards the Arctic.

These arbitrarily selected examples clearly illustrate: i) reliable measurements of surface pressure alone would be very useful for NWP data assimilation over ocean areas (Fig. 1), and ii) an accurate delineation of pressure heights should be of value even in the close vicinity of continents with a dense radiosonde network (Fig. 2). This was similarly stated by Eyre et al. (2002; cf also Tables A8 and A9):

> *Surface pressure is a primary analysis variable for global NWP, but there are no plans to measure surface pressure from space directly. This deficiency is currently addressed using a sparse network of surface ships/buoys to provide a few direct measurements of surface pressure, together with pressure gradient information from sea-surface wind measurements. However, direct measurement of surface pressure over the ocean would be valuable.*

The geographical distribution of standard temperature measurements is nearly identical to that of pressure data as they stem from the same network of SYNOP stations at the surface and from radiosounding through the free atmosphere. At any given pressure level the inclination between the gradients of geopotential height and temperature determines the degree of *baroclinicity* of the atmosphere. Areas of high baroclinity aloft, *i.e.* not aligned zones of tight height and temperature gradients (cf.

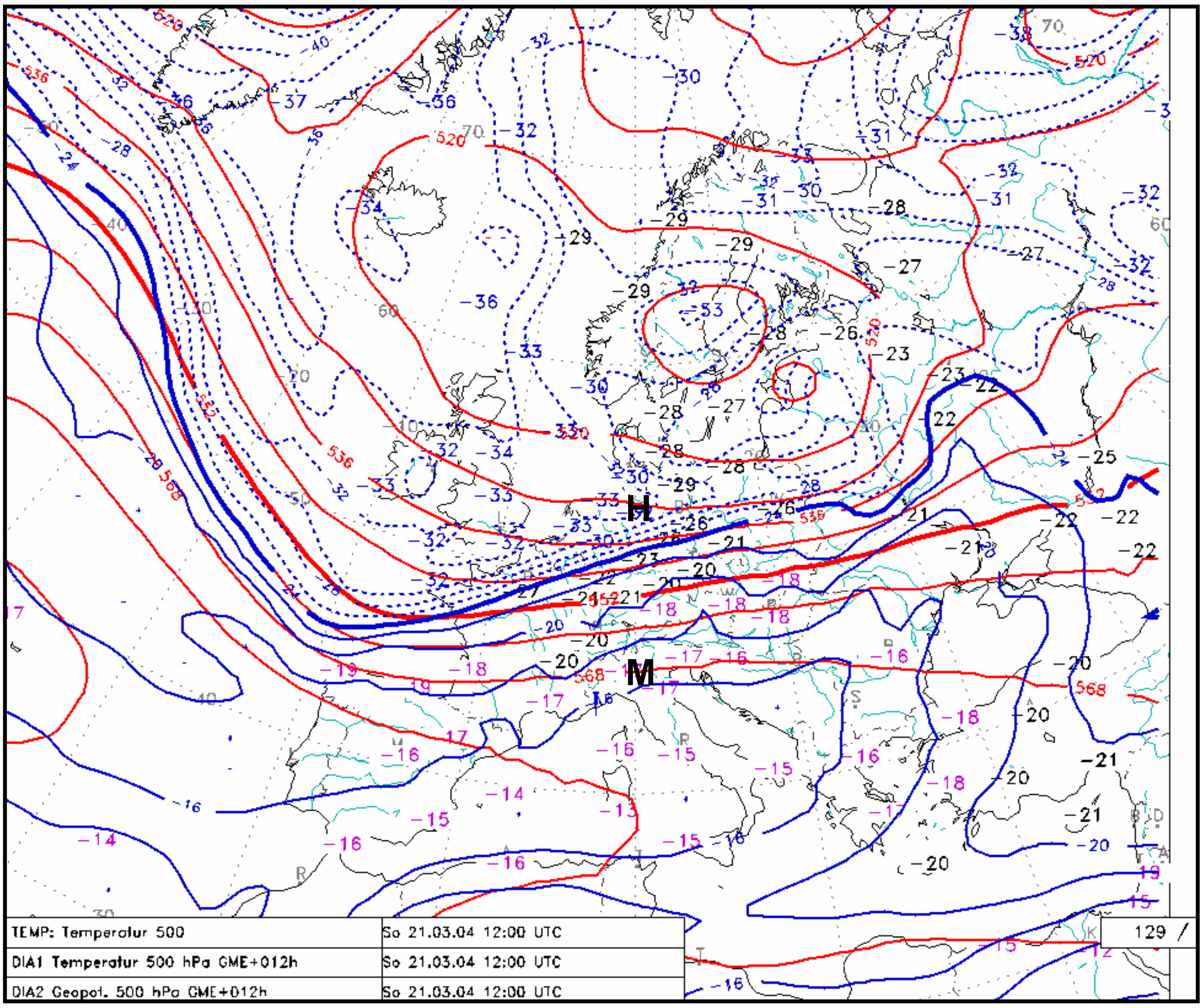


Figure 3: Fields of geopotential height (red lines) and temperature (blue lines; values below -24ºC dashed) in 500 hPa above Europe for 24 March 2004, 12 UT (12 h forecast) superimposed with temperature measurements at 129 radiosonde stations. The height gradient between Milano (M) and Hamburg (H) amounts to 400 m over 1000 km. A strong d baroclinic zone extends from the Bay of Biscay well into Poland; the angle of about 15º between the heights and temperature gradients indicates significant advection of cold air.

the arbitrarily selected example in Fig. 3), are regularly precursors of strong cyclogenesis, and hence high impact weather, at the surface (Sutcliffe, 1947). A quantitative detection of such weather active zones over the mid-latitude oceans is of everlasting importance for NWP.

Figure 4 highlights the importance of reliable height assignments for pressure levels, here for 500 hPa. Reliable height assignments in the range of 10 m would clearly help to determine bands of strong winds (jets). In the selected example the height difference of 400 m (± 200 m around the 500 hPa level’s standard height of 5.52 km) over a horizontal distance of 1000 km is equivalent to a geostrophic wind of 36 m/s.

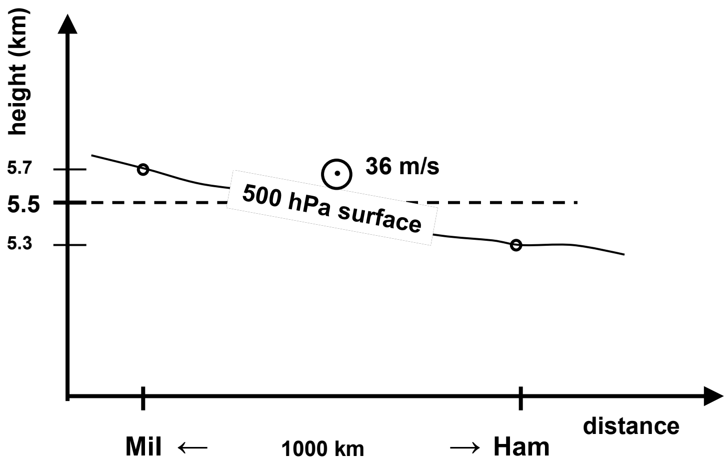


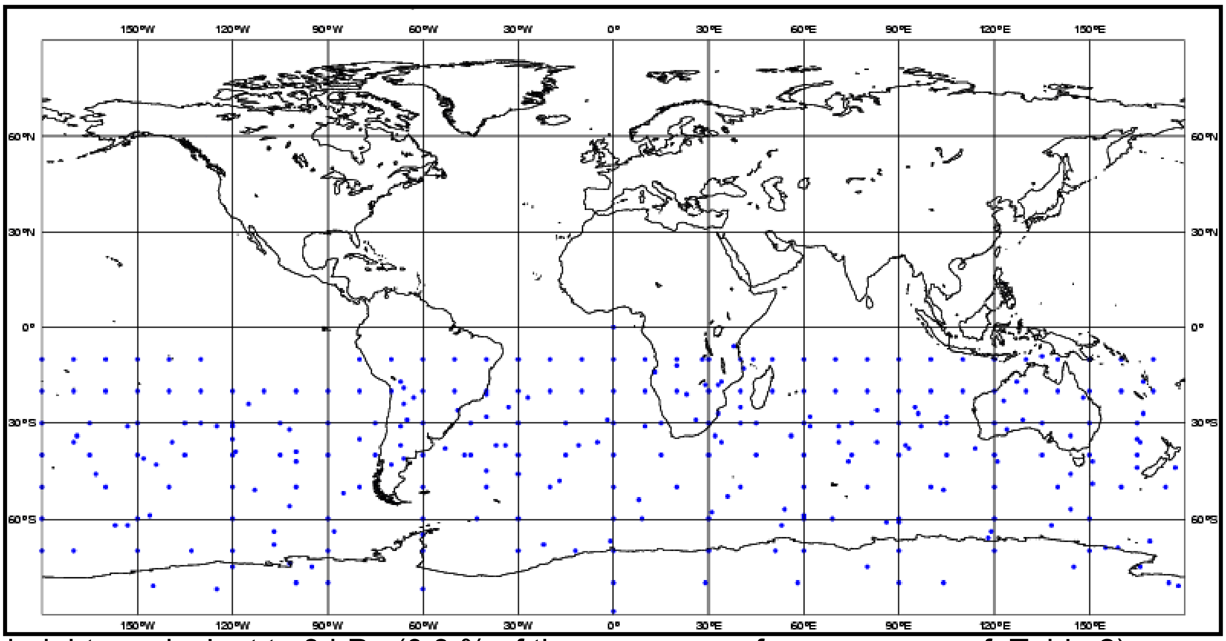
Figure 4: Schematic cross-section of the sloping 500 hPa pressure surface (as displayed through the isohypses in Figure 3) in height coordinates. A height difference of 400 m over 1000 km (as between ***Mil****ano and* ***Ham****burg) corresponds to a (geostrophic) wind out of the plane of 36 m/s.*

In contrast to pressure, temperature is already today also determined through remote sensing by passive methods. An established method is the *Advanced TIROS Operational Vertical Sounder* (ATOVS), which uses 17 infrared channels of the TIROS satellite family operated by NOAA and achieves an average vertical resolution of about 3-5 km. New passive sensors, such as the *Infrared Atmospheric Sounding Interferometer* (IASI) scheduled to fly on the METOP satellite from 2005 onwards, measure the radiation emitted by the atmosphere with much increased spectral resolution, which should improve the resolution for temperature to 1 km (ESA 2002). The *Atmospheric Infrared Radiance Sounder* (AIRS) on the AQUA satellite provides similar information already now. An inherent drawback of all these passive measurements of the terrestrial radiation lies in the fact that model generated first guess fields are necessary for the retrievals of temperature, *i.e.* the retrieved information is not really independent of the forecasting model. Furthermore, the height allocation of temperatures sensed with these novel instruments is still less accurate than conventional radiosonde measurements. When the radiance are directly fed into variational data assimilation schemes the full information content from the several thousand channels becomes prohibitive for time critical operational applications (Rabier et al., 2002).

Data assimilation

As already alluded to in the previous sections, the decisive starting point of NWP is the assimilation of all the various data which describe the state of the entire atmosphere within a certain interval of time. The *four-dimensional variational* (4d-var) assimilation technique consistently blends together all quality checked measurements from the time interval in question with a short range forecast from the previous period (*first guess*) by iterating several times through a loop forth and back (with the *adjoint* of the forecasting model) while minimizing a complex operator.

The mentioned scarce geographical coverage of pressure data on the southern hemisphere is at present ameliorated by the pragmatic construction of *pseudo Australian observations* (PAOBs) in the southern hemisphere. A typical spatial distribution is given in Figure 4. As these synthetic data obtained from a blending of conventional pressure analyses with satellite images have shown to increase the forecast skill, they are also used by northern hemisphere agencies operating global height, equivalent to 3 hPa (0.3 % of the average surface pressure; cf. Table 2).



<u>Figure 5:</u> Locations of pseudo-pressure-observations (305 for 19 December. 2003) south of 10ºS as prepared by the Australian Bureau of Meteorology. Less than half of them are regularly spaced on a 10º x 10º grid, all the others are located along weather system as cyclones and elongated fronts which show up in satellite images.

(Source: http://www.ecmwf.int/products/forecasts/d/charts/monitoring/coverage)

Table 1: Conventional temperature and pressure related variables entering the ECMWF data assimilation scheme (grouped by GTS observation type; cf. White 2002 a)

Observation type	*Observed variables*
Land surface station	Surface pressure Surface temperature (2 m height)
Sea station (ship)	Surface pressure Surface temperature (2 m height)
Upper-air sounding station	Surface temperature (2 m height) Upper-air temperature Geopotential height
Aircraft report	Temperature

models (e.g. ECMWF, DWD). Any remotely sensed surface pressure data have to compete with PAOBs. Their root-mean-square error amounts to 24 m in geopotential The conceptual details of current data assimilation methods are outlined in Kalnay (2002); their current technical realization at ECMWF is documented in White (2002a, 2002b).

As input for the construction of three-dimensional fields for pressure/geopotential height and temperature the variables listed in Table 1 are taken into account, grouped by observation type as they are transmitted through the worldwide *global telecommunication system* (GTS) operated by the national meteorological services under the auspices of the World Meteorological Organization (WMO).

Table 2: Root mean square observational errors assigned in ECWMF data assimilation for different pressure levels (cf. White, 2002a)

Level (hPa)	*1000*	*850*	*700*	*500*	*400*	*300*	*250*	*200*	*150*	*100*	*70*
Geo.height (m)	7.0	8.0	8.6	12.1	14.9	18.8	25.4	27.7	32.4	39.4	50.3
PAOB (hPa)	3.0										
Temperature (K)	1.7	1.5	1.3	1.2	1.2	1.4	1.5	1.5	1.6	1.7	1.8

At ECWMF prescribed observational errors have been derived by statistical evaluation of the performance of the observing systems, as components of the assimilation system, over a long period of operational use. The prescribed observational errors are given in the Table 2 and can be seen as a quality measure for conventional systems with which remote sensing techniques have to be compared with. It has, however, to be kept in mind that any new technology necessitates thorough test applications with current operational data assimilation schemes for a number of weather situations, if possible full seasons, before its strengths and weaknesses can be fully determined. Tabulated information can at best serve as a first guideline.

Current demands in global NWP

Fifty years after the start of operational NWP and four decades after regular satellite information is used for daily forecasting there is still much room for improvements in the task to provide better initial data. A reliable determination of the three-dimensional pressure and temperature fields remains to be of essential importance. Especially valuable are data which are fully independent of the analysis scheme and well specified concerning location and time of the measurement.

Specifically five conditions have to be met for future remote sensors. Independent measurements are sought with a certain accuracy, typical horizontal and vertical

Table 3: Threshold requirements for data accuracy, horizontal resolution Dx, accuracy of vertical positon Dz, repetition interval Dt and maximum tolerable delay for delivery into operational NWP assimilation scheme for the application ***global*** *NWP (see also Eyre et al., 2002)*

Variable	*Accuracy*	*Dx* (km)	*Dz* (km)	*Dt* (h)	*Delay* (h)
Surface pressure	3 hPa	250	–	24	4
3-dim. pressure	0.3 % of ambient value	250	0.5	24	4
Surface temperature	2 K	250	–	12	4
3-dim. temperature	3 K	500	1	24	4

*<u>Table 4:</u> "Breakthrough values" for data accuracy, horizontal resolution Dx, accuracy of vertical positon Dz, repetition interval Dt and maximum tolerable delay for delivery into operational NWP assimilation scheme for the application **global** NWP (consistent with Stuhlmann et al., 2004)*

Variable	*Accuracy*	*Dx* (km)	*Dz* (km)	*Dt* (h)	*Delay* (h)
Surface pressure	1 hPa	100	−	12	3
3-dim. pressure	0.1 % of ambient value	100	0.5	12	3
Surface temperature	1 K	50	−	12	3
3-dim. temperature	1 K	50	1	12	3

resolutions, a repetition interval and, very important, a maximum tolerable delay for delivery into operational NWP schemes. The corresponding threshold values differ considerably for *global* or *regional* weather forecasting. The respective estimates for global NWP applications are collected in Table 3. Height resolved pressure data would enable the determination of the geopotential, but the demands for of height allocation (0.5 km or better) and accuracy (0.3 % of the ambient value varying between 1000 and 200 hPa within the troposphere are demanding. It would be of great use to resolve, for example, the 500 hPa height difference between of 400 m over a distance of 1000 km between Hamburg and Milano (cf. Fig. 3). The surface

value of 3 hPa corresponds to the current observational height error of PAOB data (24 m; Table 2). Some years ahead, however, new instruments appear only useful for global NWP if they meet the "breakthrough levels" given in Table 4.

Global NWP assumes in good approximation that the atmosphere is an ideal gas in hydrostatic balance. Consequently the depth of a certain vertical layer ($z_1 - z_0$) is linked to its top and bottom pressures (p_1 and p_o)and its mean temperature (T_m)

$$p_1 = p_0 \ \exp\{g\ (z_1 - z_0)/(R\ T_m)\} \qquad (1)$$

where g denotes the Earth's gravity and R the gas constant. Assuming that the layered temperature profile is sufficiently known, *e.g.* through passive sensors, the (active) measurement of surface pressure provided a firm basis for the successive height determination of specified pressure levels (cf. Fig. for the 500 hPa level). Alternatively eq. (1) can be used for cross-checking of remotely sensed temperature and pressure profiles.

Regarding the overall instrument accuracy it has to be noted that measurement biases can be detected rather well by the assimilation systems when they stem mostly from the instrument characteristics. The bias in surface pressure should be less than the current error level for PAOBs (3 hPa). Moreover, such a systematic error should not be much influenced by the prevailing surface temperatures, *e.g.* distinct airmasses on either side of frontal zones, as such features are to be resolved by the data assimilation.

The altitude range of interest for NWP covers troposphere and lower stratosphere, *i.e.* from the ground to a height of about 25 km (pressure range: 1050 to 20 hPa), with the emphasis at the surface and in the tropopause region. The desired data coverage should be global with about 5000 data points (or profiles) along equally spaced overpasses (if a lower earth orbit is assumed). Nadir measurements without across track scanning are sufficient. Ongoing experiences which direct remote sensing of flow and their impact for NWP have to be used (cf. test campaigns for ADM-Aeolus in the framework of THORPEX; Shapiro and Thorpe, 2003).

For comparison, Table 5 lists the requirements, which at present are considered as the limit in *global* NWP beyond which no further gain can be expected as well as the threshold for useful contributions for *regional* NWP which deals with much smaller areas and shorter periods of time.

Table 5: Threshold requirements for data accuracy, horizontal resolution Dx, vertical resolution Dz, repetition interval Dt and maximum tolerable delay for delivery into operational NWP assimilation scheme for the application ***regional*** *NWP*

Variable	*Accuracy*	*Dx* (km)	*Dz* (km)	*Dt* (h)	*Delay* (h)
Surface pressure	0.5 hPa	15	−	1	1
Surface temperature	0.5 K	15	−	1	1
3-dim. temperature	0.5 K	15	0.5	1	1

Tables 3 to 5 contain in condensed format the published specifications published by the World Meteorological Organization (WMO). For the sake of comparison the differently stated requirements for climate analysis and NWP applications are listed in the appendix. In the next section, however, it is argued that in the context of this document the global NWP requirements dominate those of both domains neighbouring in scale, climate analysis and regional NWP.

We conclude that the numerical weather prediction on a *global* scale has large demand for active remote sensing of basic atmospheric parameters from future satellites. Pressure information is of higher importance than temperature, as it reflects the flow field and is not directly observed from space as yet. The NWP community acts as an immediate user of additional data. Climatological studies necessitate at the outset multi-year time series (which are mostly taken from the NWP centres archives, *e.g.* re-analysis datasets ERA-40 data from ECMWF or NCEP-50 from the US weather service, rather from 'non-NWP' measurements of a reduced accuracy).

Observational requirements for global NWP

Summarizing the discussion in the previous sections generic requirements for the sampling of temperature and pressure from space borne instruments can be listed. Four vertical layers are distinguished (as, *e.g.*, in Floury and Fuchs, 2001): lower troposphere (LT), higher troposphere (HT), lower stratosphere (LS) and higher stratosphere (HS) for temperature with the pressure bands as given in Table 6, and the Earth's surface, LT, HT and LS for pressure as listed in Table 7. For pressure the determination of reliable surface values appears to be of highest importance to improve the semi-empirical PAOB data of the southern oceans, while sufficiently accurate measurements of the high stratospheric values below 10 hPa are not considered as feasible.

Global numerical weather prediction is seen as the central focus for application. Implicitly this also includes the larger scale application of climatological monitoring and smaller scale regional NWP demands for the following reasons: *i)* climatological

Table 6: Observational requirements for ***global NWP*** *for space borne temperature sensors broken down by the atmospheric layers Lower Trosposphere (****LT****), Higher Trosposphere (****HT****), Lower Stratosphere (****LS****), and Higher Stratosphere (****HS****).*

Parameter		***Temperature***			
Altitude range		**LT**	**HT**	**LS**	**HS**
pressure height	[hPa]	1000–500	500–100	100–10	10 – 1
approx. height range	[km]	0 – 5	5 – 15	15 – 35	35 – 50
Vertical sampling[1]	[km]	1	1	2	3
Height assignment	[km]	0.1	0.1	0.2	0.3
Horizontal domain		global			
Horizontal sampling[2]	[km]	50	100	200	250
Dynamic range	[K]	180 - 300			
Precision[3] (1 standard deviation)	[K]	1	1	2	2
Bias	[K]	< 0.5	< 0.5	< 0.5	< 0.5
Observation cycle[4]	[h]	12	12	12	12
Timeliness[5]	[h]	3	3	3	3

[1] vertical sampling requirement for regional NWP = 0.5 km
[2] horizontal sampling requirement for regional NWP = 15 km
[3] precision requirement for regional NWP = 0.5 °K
[4] observation cycle for regional NWP = 1 h
[5] timeliness for regional NWP = 1 h

analyses using basic meteorological variables like temperature and pressure necessicate consistent time series exceeding a decade; these are currently established at large weather centres (*e.g.* ECMWF or NCEP) by re-analyzing 15, 40 or even 50 year long spans of raw data, including satellite observations as far as they are available; this means that even in the future long-term data sets for climate analysis will be determined from global weather data, the observational requirements of which are steered by NWP applications; *ii)* regional NWP uses high resolution limited area models (current horizontal grid mesh below 10 km); they are nested in global NWP models, which provide the initial data and the forecast boundary values for the entire forecast period; the impact of space borne sensors to regional NWP will also in the future follow the link via global NWP, while future mesoscale data assimilation will focus on surface based remote sensing (*e.g.* by precipitation radar

*Table 7: Observational requirements for **global NWP** for space borne pressure sensors broken down the Earth's **surface** and the atmospheric layers Lower Trosposphere (**LT**), Higher Trosposphere (**HT**), and Lower Stratosphere (**LS**).*

Parameter	***Pressure***			
Altitude range	**surface**	**LT**	**HT**	**LS**
pressure height [hPa]		1000-500	500-100	100-10
approx. height range [km]		0 – 5	5 – 15	15 – 35
Vertical sampling [km]		1	1	2
Height assignment [km]	0.01	0.01	0.01	0.01
Horizontal domain	global			
Horizontal sampling[1] [km]	50	50	100	200
Dynamic range [hPa]	1050-950	1050-500	500-100	100-10
Precision[2] (1 standard deviation) [hPa]	<1	0.6	0.2	0.1
Bias [hPa]	<0.5	<0.5	<0.2	<0.1
Observation cycle[3] [h]	12	12	12	12
Timeliness[4] [h]	3	3	3	3

[1] horizontal sampling requirement for regional NWP = 15 km
[2] surface pressure requirement for regional NWP = 0.5 hPa
[3] observation cycle for regional NWP = 1 h
[4] timeliness for regional NWP = 1 h

networks; we also note that regional NWP mainly concerns well instrumented land areas).

Inspired by the example given in Figures 3 and 4, special emphasis is put on a well specified height assignment of the envisaged future space instruments. When satellite determined vertical profiles come close to the still unmatched standard of conventional radiosonde profiles concerning a height assignment reliable in the order of 100 to 10 m, a major breakthrough in NWP applications can be expected. Currently a vast number of satellite data enter the NWP data assimilation schemes, but only a small fraction of independent pieces of information are retained, while all quality checked radiosonde profile provide up to 100 independent data points in the vertical although they are only counted as a single entry. For this reason, active remote sensing with advanced lidar techniques appears to promising.

Table 8: Observational requirements for surface pressure for nowcasting, regional and global NWP applications according to the EUMETSAT study. Breakthrough values lie between threshold and the ambitious target specifications.

Surface pressure	Accuracy (threshold/target)	Spatial resolution (thres./tar.)	Repeat cycle (thres./tar.)	Timeliness (thres./tar.)	Breakthrough
Now-casting	2 / 1 hPa	10 / 1 km	30 / 10 min.	30 / 10 min.	2 hPa, 10 km, 30 min.
NWP Regional	1 / 0.1 hPa	50 / 3 km	3 / 0.5 h	No spec	1 hPa, 30 km, 3 hrs.
NWP Global	3 / 0.5 hPa	250 /15 km	12 / 1 h	4 / 1 h	1 hPa, 100 km, 6 h

Consistency with previous EUMETSAT study

The set of observational requirements for the surface pressure are to be juxtaposed with the findings of a recent EUMETSAT study, which was provided by ESA (Table 8). These requirements cover the categories threshold (thres.), target (tar.) and breakthrough for the categories now-casting, regional, and global NWP independently. We assign highest relevance to global NWP (see argumentation on pp. 17/18) and note that the surface pressure breakthrough requirements for global NWP from EUMETSAT study are close to our findings as given in Table 7. The horizontal resolution should be close to the equivalent grid size of current global models (between 100 and 50 km). However, more important than distance between neighbouring measurements is the question over how large an area such data are averaged: data points separated by 100 km still have breakthrough potential, if they are representative for distances of the order 10 km, so that existing gradients in the atmosphere are not smeared out too much by the retrieval method.

Treatment of surface pressure data at ECMWF and recommendation

To corroborate the figures given in Table 7, in particular for surface pressure, data assimilation experts at ECMWF were asked to communicate the current status of affairs at the centre. They gave detailed advice about the present quality of surface pressure observations, which can be summarized as follows:

1) The current analysis errors specified in data assimilation are below 1 hPa and depend somewhat on station type (manual, automatic) and location (land, sea);
2) PAOBs are no longer in use;
3) The spatial patterns of pressure analysis errors were estimated by a month long data assimilation experiment using a ten member ensemble (see Figure 6);
4) The impact of conventional surface data on NWP results was recently summarized by J.-N. Thépaut (available via the web under http://www.wmo.int/files/www/GOS/Alpbach2004/1B_2ThepautJeanNoel.pdf)

It clearly appears that current state-of-the-art NWP archives allow to retrieve the pressure at sea level with an average accuracy of about 0.7 hPa (equivalent to an height error of about 6 m). At the 850 hPa level the mean height allocation error is less than 10 m. These data could be made available for the retrieval of Lidar sensed CO_2 columns. Nevertheless, surface pressure sensed from space still appears to be very useful for direct NWP applications, if accuracies of significantly better than 1 hPa can be obtained for the problem regions over Africa and the Southern Ocean around Antarctica.

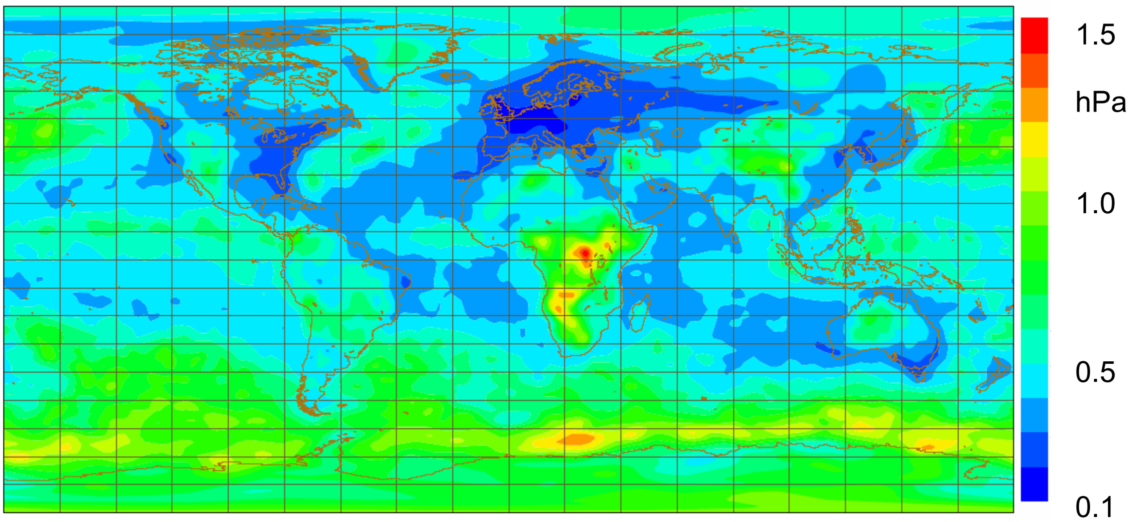


Figure 6: Spatial patterns of the current global surface pressure analysis errors estimated from a month long data assimilation experiment (Oct. 2000) using a ten member ensemble. Although the absolute values suffer a scaling uncertainty of ±15% the regions of lowest accuracy lie over land in central Africa, the Himalayas and Antarctica, and spatially much more extended over the Pacific and Southern Oceans.

Courtesy of H. Hersbach and M. Fisher, ECMWF

The following summary by J.-N. Thépaut (2004; personal communication of a not yet published manuscript) further underlines the fundamental importance of surface pressure for NWP applications (highlighting by Hans Volkert):

Conclusions

A number of low resolution and high resolution Observing System Experiments (OSEs) has been performed at ECMWF to assess some aspects of the relevance of the surface observing system. With the precautions required due to the usual limitations of the OSEs, (in particular the always too short periods of investigations, the verification criteria, the simplicity of the scenario, etc…), the LOW-OSEs seem to indicate that:

1. *Surface data are an* ***essential*** *element of the current Observing System*
2. ***Some*** *surface pressure observations (over sea* ***and*** *land) are* ***absolutely essential*** *to anchor the surface pressure field*
3. *Surface wind observations provide too partial surface pressure information to be used in isolation*
4. *A* ***degradation*** *of the accuracy of the current surface pressure Observing System would have a* ***detrimental impact*** *on forecast performance (this may entail that there is very little scope to obtain surface pressure information from space at the accuracy by currently required by NWP systems)*
5. *In presence of surface wind observations over sea, a reduced number of surface pressure observations (for example ships - note that the symmetric experiment withdrawing ships only has not been performed -) seems sufficient to obtain "good" forecast performance*

HIGH-OSEs that have been run in a more realistic and challenging context show that:

1. *Even in a NWP system overwhelmed by satellite observations, the conventional sea surface network provided by buoys and ships has* ***on average a noticeable positive impact***
2. *Surface observations over sea can have a* ***very large positive impact*** *on specific* ***synoptic cases*** *(large negative impacts were not found during the period under investigation)*
3. *Ships and buoys show a similar impact on the ECMWF forecast performance*

Overall, these studies confirm the high level of ***complementarity*** *of the space and terrestrial networks, despite an escalating use of satellite data in modern global NWP assimilation systems.*

It can therefore be truly recommended to seriously consider active remote sensing of surface pressure from space-borne platforms in order to further complement the array of data which is necessary to further develop operational global NWP applications as well as a reliable monitoring of the atmosphere for detecting signals of climate change.

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Appendix: Published tables for requirements and instruments

The following tables characterize the current observational requirements for various atmospheric variables and applications as well as the instrument characteristics for current and planned satellite missions. The entry points for the sources (web based questionnaire at WMO in Geneva) are specified.

Temperature	Hor. Res. [km]	Vert. Res. [km]	Obs. Cycle [h]	Accuracy °K	Delay [h]	Confidence	Use
Surface	25-100	/	3-12	0.2 - 0.5	24-72	Speculative	Terrestrial climate
Profile (HS) &Mesosphere	100-500	2-3	2-6	1-3	3-12	Firm	Terrestrial climate
Profile (LS)	100-500	0.1-0.5	3 - 6	0.5 - 2	3 -12	Firm	AOPC
Profile (HT)	100-500	0.1-0.5	3 - 6	0.5 - 2	3 - 12	Firm	AOPC
Profile(LT)	100-500	0.1 - 2	3 - 6	0.5 - 2	3 -12	Firm	AOPC

*Table A1: Observational requirements for global atmospheric temperature measurements for **climate analysis** as specified by **CGOS**; HS= high stratosphere, LS = Low Stratosphere, HT = high troposphere, LT= low troposphere. (source entry via: http://www.wmo.ch/index-en.html)*

Temperature	Hor. Res. [km]	Vert. Res. [km]	Obs. Cycle [h]	Accuracy °K	Delay [h]	Confidence	Use
Surface	100-500	/	12 - 24	0.2 - 0.5K	24 - 48	Tentative	ACSYS
Profile (HS) & Mesosphere	50- 500	5 - 10	3 -12	1 - 3	720 -1440	Reasonable	Global modelling
Profile (HS) & Mesosphere	50-500	0.5 - 2	6 - 72	0.5 - 1	24 -168	Reasonable	SPARC
Profile (LS)	50-500	1 - 3	3 -12	0.5 - 3	720 - 1440	Reasonable	Global modelling
Profile (LS)	50-500	0.5 - 2	6 - 72	0.5 - 1	24 -168	Reasonable	SPARC
Profile (HT)	50-500	1 - 3	3 - 12	0.5 - 3	720 -1440	Reasonable	Global modelling
Profile(HT)	50-200	0.5 - 2	6 - 72	0.5 - 1	24 - 168	Reasonable	SPARC
Profile (LT)	50-500	0.3 - 3	3 -12	0.5 - 3	720 - 1440	Reasonable	Global modelling
Profile (LT)	50 - 500	0.5 - 2	6 - 72	0.5 - 1	24 - 168	Reasonable	SPARC

*Table A2: Observational requirements for global atmospheric temperature measurements for **climate analysis** as specified by **WCRP**; HS= high stratosphere, LS = Low Stratosphere, HT = high troposphere, LT= low troposphere. (source entry via: http://www.wmo.ch/index-en.html)*

Temperature	Hor. Res. [km]	Vert. Res. [km]	Obs. Cycle [h]	Accuracy [°K]	Delay [h]	Confidence	Use
Surface	10-100	/	.1 - 12	0.5 - 2	1 - 4	Firm	Synoptic meteorology
Surface	50-250	/	1 -12	0.5 - 2	1 - 4	Reasonable	Global NWP
Surface	10-250	/	0.5 -12	0.5 -2	0.5 - 2	Reasonable	Regional NWP
Surface	5 - 20	/	0.25 - 1	0.5 - 1	0.25 - 0.5	Reasonable	Nowcasting
Profile (HS) & Mesosphere	50 - 500	1 - 3	1 -12	0.5 - 5	1 - 4	Reasonable	Global NWP
Profile(LS)	50 - 500	1 - 3	1 - 12	0.5 - 3	1 - 4	Firm	Global NWP
Profile (LS)	20 - 200	1 - 3	3 - 12	0.5 -3	1 -3	Firm	Synoptic meteorology
Profile (LS)	10 - 500	1 - 3	0.5 - 12	0.5 - 3	0.5 - 2	Firm	Regional NWP
Profile (HT)	10 - 500	1 - 3	0.5 - 12	0.5 - 3	0.5 - 2	Firm	Regional NWP
Profile(HT)	20 - 200	1 - 2	3 - 12	0.5 - 3	1 - 3	Firm	Synoptic meteorology
Profile(HT)	50 - 500	1 - 3	1 - 12	0.5 - 3	1 - 4	Firm	Global NWP
Profile(LT)	5 - 200	0.5 - 1	0.25 - 1	0.5 - 2	0.08 - 0.5	Firm	Nowcasting
Profile(LT)	10 - 500	0.3 - 3	0.5 - 12	0.5 - 3	0.5 - 2	Firm	Regional NWP
Profile (LT)	20 - 200	0.1 - 2	3 - 12	0.5 - 3	1 - 3	Firm	Synoptic meteorology
Profile(LT)	50 - 500	0.3 - 3	1 - 12	0.5 - 3	1 - 4	Firm	Global NWP

*Table A3: Observational requirements for atmospheric temperature measurements for **NWP purposes** as tspecified by **WMO**; HS= high stratosphere, LS = Low Stratosphere, HT = high troposphere, LT= low troposphere. (source entry via:* http://www.wmo.ch/index-en.html *)*

Surface Pressure	Hor. Res. [km]	Vert. Res. [km]	Obs. Cycle [h]	Accuracy hPa	Delay [h]	Confidence	Use
over land	50 - 250	/	1 - 12	0.5 - 2	1 - 4	Firm	Global NWP
over land	10 - 250	/	0.5 - 12	0.5 -1	0.5 - 2	Firm	Regional NWP
over see	50 - 250	/	1 -12	0.5 - 2	1 - 4	Firm	Global NWP
over see	10 - 250	/	0.5 -12	0.5 -1	0.5 - 2	Firm	Regional NWP

*Table A4: Observational requirements for atmospheric surface pressare measurements for **NWP purposes** as specified by **WMO**; HS= high stratosphere, LS = Low Stratosphere, HT = high troposphere, LT= low troposphere. (source entry via:* http://www.wmo.ch/index-en.html *)*

Atmospheric temperature profile - Lower stratosphere (LS)

Instrument	HRes	VRes	Acc	ObsCy	Delay	Comments	Source
AIRS	50 km	1 km	1 K	12 h	24 h		14/08/01 10:33:19 NASA
AMSU-A	50 km	2 km	2 K	12 h	2 h		11/07/01 12:35:58 NOAA
ATMS	50 km	2 km	2 K	12 h	2 h		11/07/01 13:03:14 NOAA
CHAMP GPS Sounder	200 km	1 km	0.5 K	24 h	12 h	Delay: 1-12 h	11/09/01 15:23:33 DLR
CrIS	25 km	2 km	1 K	12 h	2 h		11/07/01 14:23:09 NOAA
GPSOS	1000 km	1 km	1 K	12 h	2 h		11/07/01 14:38:44 NOAA
GRAS	300 km	1 km	1 K	120 h	3 h		17/07/01 11:32:35 EUMETSAT
HiRDLS	400 km	1 km	1 K	12 h	24 h		16/10/98 10:09:25 NASA
HIRS/2	80 km	2 km	2.5 K	12 h	2 h		11/07/01 14:47:43 NOAA
HIRS/3	40 km	2 km	2.5 K	12 h	2 h		13/08/99 11:05:11 NOAA
HIRS/4	40 km	2 km	2.5 K	12 h	2 h		17/07/01 11:20:14 NOAA
IASI	25 km	2.5 km	1 K	12 h	3 h		17/07/01 11:31:41 EUMETSAT
ILAS-II	300 km	1 km	Missing	Missing	Missing		18/09/98 18:10:14 NASDA
MIPAS	300 km	3 km	Missing	36 h	3 h		27/09/98 14:27:55 ESA
MLS (EOS-Aura)	200 km	2 km	3 K	12 h	24 h		16/10/98 09:27:51 NASA
MSU	160 km	2 km	2.5 K	12 h	2 h	used with HIRS	17/07/01 11:27:52 NOAA
OSIRIS	Missing	Missing	7 K	Missing	Missing	Vertical Resolution: Lower Stratosphere <2km, between 15 and 35 km. Horizontal Resolution: 750 km between 15 and 40 km. Accuracy +-7K.	28/06/01 14:47:57 CSA
SAGE III	100 km	1 km	2 K	48 h	24 h	Accuracy varies between solar and lunar occultation measurements	27/10/98 16:55:41 NASA
SOFIS	300 km	1 km	Missing	Missing	Missing		18/04/00 18:10:55 NASDA
SOPRANO	50000 km	3 km	Missing	3 h	Missing		27/09/98 15:05:04 ESA
Sounder	30 km	2 km	2.5 K	1 h	0.5 h		11/07/01 15:41:46 NOAA
SSM/T-1	175 km	Missing	2.25 K	Missing	Missing		15/09/99 11:07:44 NOAA
SSU	200 km	2 km	2 K	12 h	2 h		17/07/01 12:19:15 NOAA
TES	169 km	6 km	2 K	96 h	24 h	Error budgets different for limb mode and nadir mode	27/10/98 17:00:54 NASA
TOVS (HIRS/2 + MSU + SSU)	80 km	2 km	2.5 K	12 h	2 h		11/07/01 15:49:16 NOAA

Table A5: Current and planned instruments that measure the atmospheric temperature profile in the lower stratosphere (LS)
. (source entry via :http://alto-stratus.wmo.ch/sat/stations/_asp_htx_idc/ParamInst.asp)

Atmospheric temperature profile – Higher troposphere (HT)

Instrument	HRes	VRes	Acc	ObsCy	Delay	Comments	Source
AIRS	50 km	1 km	1 K	12 h	24 h	Accuracy 1 k	14/08/01 10:31:50 NASA
AMSU-A	50 km	1 km	2 K	12 h	2 h		11/07/01 12:35:25 NOAA
ATMS	50 km	1 km	2 K	12 h	2 h		11/07/01 13:02:49 NOAA
ATOVS (HIRS/3 + AMSU + AVHRR/3)	40 km	1 km	2 K	12 h	2 h		11/07/01 13:34:11 NOAA
CHAMP GPS Sounder	200 km	1 km	0.5 K	24 h	12 h	Delay: 1-12 h	11/09/01 15:23:10 DLR
CrIS	25 km	1 km	1 K	12 h	2 h		11/07/01 14:27:47 NOAA
GPSOS	1000 km	1 km	1 K	12 h	2 h		11/07/01 14:38:07 NOAA
GRAS	300 km	1 km	1 K	120 h	3 h		17/07/01 11:32:32 EUMETSAT
HiRDLS	400 km	1 km	2 K	12 h	24 h		16/10/98 10:09:24 NASA
HIRS/2	80 km	1 km	2.5 K	12 h	2 h		11/08/99 15:59:17 NOAA
HIRS/3	40 km	1 km	2.5 K	12 h	2 h		13/08/99 11:05:03 NOAA
HIRS/4	40 km	1 km	2.5 K	12 h	2 h		17/07/01 11:14:23 NOAA
IASI	25 km	2 km	K	12 h	3 h		17/07/01 11:31:09 EUMETSAT
ILAS-II	300 km	1 km	Missing	Missing	Missing		18/09/98 18:01:40 NASDA
MIPAS	300 km	3 km	Missing	36 h	3 h		27/09/98 14:27:30 ESA
MLS (EOS-Aura)	200 km	2 km	3 K	12 h	24 h		16/10/98 09:26:03 NASA
MODIS	1 km	Missing	1.5 K	12 h	Missing		14/08/01 10:45:58 NASA
MSU	160 km	1 km	2.5 K	12 h	2 h	used with HIRS	17/07/01 11:28:01 NOAA
SAGE III	100 km	1 km	2 K	48 h	24 h	Accuracy varies between solar and lunar occultation measurements	27/10/98 16:56:39 NASA
SOFIS	300 km	1 km	Missing	Missing	Missing		18/04/00 18:10:23 NASDA
Sounder	30 km	1 km	2.5 K	1 h	0.5 h		11/07/01 15:41:40 NOAA
SSM/T-1	175 km	Missing	2.25 K	Missing	Missing		15/09/99 11:07:17 NOAA
MIS	50 km	1 km	2 K	12 h	3 h		17/07/01 12:12:36 NOAA
TES	169 km	6 km	2 K	96 h	24 h	Error budgets different for limb mode and nadir mode	27/10/98 17:00:53 NASA
TOVS (HIRS/2 + MSU + SSU)	80 km	1 km	2 K	12 h	2 h		11/07/01 15:47:28 NOAA
VAS	100 km	1 km	2.5 K	1 h	h		11/07/01 15:50:50 NOAA

Table A6: Current and planned instruments that measure the atmospheric temperature profile in the higher troposphere (HT)
. (source entry via :http://alto-stratus.wmo.ch/sat/stations/_asp_htx_idc/ParamInst.asp)

Atmospheric temperature profile - Lower troposphere (LT)

Instrument	HRes	VRes	Acc	ObsCy	Delay	Comments	Source
174-K	Missing	Missing	Missing	Missing	Missing		15/03/02 12:34:06 WMODBA
AIRS	50 km	1 km	1 K	12 h	24 h	Accuracy 1 K	14/08/01 10:31:43 NASA
AMSU-A	50 km	1 km	2 K	12 h	2 h		11/07/01 12:35:04 NOAA
ATMS	50 km	1 km	2 K	12 h	2 h		11/07/01 13:02:02 NOAA
ATOVS (HIRS/3 + AMSU + AVHRR/3)	40 km	1 km	1.5 K	12 h	2 h		11/07/01 13:33:14 NOAA
ATSR	Missing	Missing	issing	Missing	Missing		06/12/01 15:00:08 WMODBA
ATSR-2	Missing	Missing	Missing	Missing	Missing		06/12/01 15:09:15 WMODBA
CHAMP GPS Sounder	200 km	0.5 km	1 K	24 h	12 h	Vert. Resolution: 0.2-0.5 km, Delay 1-12 h	11/09/01 15:23:03 DLR
CHRIS	Missing	Missing	Missing	Missing	Missing		19/02/02 09:08:24 WMODBA
CrIS	25 km	1 km	1 K	12 h	2 h		11/07/01 14:29:18 NOAA
GIFTS	Missing	Missing	Missing	Missing	Missing		07/12/01 10:29:43 WMODBA
GOLPE	Missing	Missing	Missing	Missing	Missing		22/03/02 10:31:35 WMODBA
GOMOS	Missing	Missing	Missing	Missing	Missing		07/12/01 15:51:45 WMODBA
GPS	Missing	Missing	Missing	Missing	Missing		03/02/02 12:12:24 WMODBA
GRAS	300 km	1 km	2 K	120 h	3 h		17/07/01 11:32:30 EUMETSAT
HALOE	Missing	Missing	Missing	Missing	Missing		06/02/02 11:29:20 WMODBA
HIRS/2	80 km	1 km	2.5 K	12 h	2 h		11/08/99 15:59:15 NOAA
HIRS/3	40 km	1 km	.5 K	12 h	2 h		13/08/99 11:05:02 NOAA
HIRS/4	40 km	1 km	2.5 K	12 h	2 h	all HIRS/4 entries same as HIRS/3	17/07/01 11:14:05 NOAA
HRDI	Missing	Missing	Missing	Missing	Missing		06/02/02 11:29:19 WMODBA
IASI	25 km	1 km	1 K	12 h	3 h		17/07/01 11:31:07 EUMETSAT
IIR	Missing	Missing	Missing	Missing	Missing		07/12/01 10:29:43 WMODBA
IKFS-2	Missing	Missing	Missing	Missing	Missing		15/03/02 12:25:18 WMODBA
IVISSR (FY-2)	Missing	Missing	Missing	Missing	Missing		06/12/01 16:45:25 WMODBA
MLS	Missing	Missing	Missing	Missing	Missing		06/02/02 11:29:19 WMODBA
MODIS	5 km	Missing	0.15 K	12 h	Missing		14/08/01 10:45:56 NASA
MSU	160 km	1 km	2.5 K	12 h	2 h	used with HIRS	17/07/01 11:28:09 NOAA
MTVZA	Missing	Missing	Missing	Missing	Missing		15/03/02 12:34:06 WMODBA
SAGE I	Missing	Missing	Missing	Missing	Missing		22/02/02 13:31:08 WMODBA
SAGE II	Missing	Missing	Missing	Missing	Missing		19/02/02 09:41:29 WMODBA
SMR	Missing	Missing	Missing	Missing	Missing		22/03/02 10:31:35 WMODBA
Sounder	30 km	1 km	2.5 K	1 h	0.5 h		11/07/01 15:41:36 NOAA
Sounder (INSAT)	Missing	Missing	Missing	Missing	Missing		16/05/02 10:25:49 WMODBA
SSM/T-1	175 km	Missing	2.25 K	Missing	Missing		15/09/99 11:06:47 NOAA
SSMIS	50 km	1 km	2 K	12 h	3 h		17/07/01 12:12:09 NOAA
TES	169 km	6 km	2 K	96 h	24 h	Error budgets different for limb mode and nadir mode	27/10/98 16:59:15 NASA
TOVS (HIRS/2 + MSU + SSU)	80 km	1 km	2 K	12 h	2 h		11/07/01 15:47:22 NOAA
VAS	100 km	1 km	2.5 K	1 h	1 h		11/07/01 15:51:19 NOAA
WINDII	Missing	Missing	Missing	Missing	Missing		06/02/02 11:29:19 WMODBA

Table A7: Current and planned instruments that measure the atmospheric temperature profile in the lower troposphere (LT)
. (source entry via :http://alto-stratus.wmo.ch/sat/stations/_asp_htx_idc/ParamInst.asp)

Air pressure over sea surface

Instrument	HRes	VRes	Acc	ObsCy	Delay	Comments	Source
ATMS	Missing		Missing	Missing	Missing		22/08/01 11:14:45 NOAA
CPR (Cloudsat)	1 km		30 hPa	Missing	Missing		08/12/99 15:44:53 NASA
CrIS	Missing		Missing	Missing	Missing		22/08/01 11:15:51 NOAA
MESSR	0.05 km		Missing	Missing	Missing		28/06/01 15:11:35 NASDA

Table A8: Current and planned instruments that measure the atmospheric surface pressure over sea
. (source entry via :http://alto-stratus.wmo.ch/sat/stations/_asp_htx_idc/ParamInst.asp)

Air pressure over land surface

Instrument	HRes	VRes	Acc	ObsCy	Delay	Comments	Source
ATMS	Missing		Missing	Missing	Missing		22/08/01 11:14:38 NOAA
CrIS	Missing		Missing	Missing	Missing		22/08/01 11:15:47 NOAA

Table A9: Current and planned instruments that measure the atmospheric surface pressure over land
. (source entry via :http://alto-stratus.wmo.ch/sat/stations/_asp_htx_idc/ParamInst.asp)