Joint ECMWF/EUMETSAT Workshop on the Use of Satellite Data in Operational Numerical Weather Prediction: 1989-1993

INTRODUCTION

Errors in weather forecasts frequently arise from lack of observational data in critical areas, particularly over the oceans. Quantitative satellite-based observations represent the best means for improving the accuracy of the initial state in Numerical Weather Prediction (NWP). ECMWF and EUMETSAT have a common interest in ensuring that the most accurate data is provided for weather analysis, and that the data is used effectively. Satellite data finds many applications in now-casting and very short-range forecasting; these applications are not discussed here. Instead, the purpose of the present workshop is to review the quantitative use of satellite data for NWP, particularly in the medium range.

Impact of Satellite Data on NWP

The decade of the 80's has been a period of relative stability in the operational systems monitoring the global atmosphere, with cloud track winds provided from five geostationary satellites, and temperature/humidity soundings provided by the NOAA polar orbiters. By contrast, the 90s will see many developments in the availability of satellite data for operational meteorology.

The current operational satellite observation systems were developed for the Global Weather Experiment in 1979, and have since continued in operational use. Observation system experiments with GWE data in the early 80s generally showed distinct positive impact of the satellite data on weather forecasts.

Over the last decade there has been considerable improvement in the techniques of numerical weather prediction, with significant gains in forecast skill. Over the same period there has been little development in operational instrument technology, and only modest improvements in the retrieval techniques used to convert satellite radiance measurements to geophysical quantities. These facts have led to a deterioration in the relative information content of satellite data.

The relative information content of an observational system is related to the ratio of two uncertainties: the uncertainty in the analysis after we have used all the data, compared to the uncertainty if we used all the data except the system in question. The general improvement in assimilation and modelling techniques has meant that it is now more difficult to demonstrate a positive impact of satellite data. Modelling and assimilation developments, which were not accompanied by developments in observing or retrieval methods, have therefore tended to reduce the information content of satellite data relative to other information sources.

Retrieval Methods for Sounding Data

A prime motivation for the workshop was the need to review the possibilities for better exploitation of wind, temperature, and humidity data from current and imminent satellite systems.

We see the need for two main lines of development in the use of sounding data. There is still considerable room for improvement in conventional sounding-retrieval methods (which do not use a model first-guess). These retrieval methods are independent of a forecast model and are likely to be most valuable in areas where the model first-guess is inaccurate and where the relative information content of the satellite data is high. Considerable improvement is possible through better cloud filtering,(one of the most critical problems for retrieval methods), better air-mass classification, and better radiance tuning.

In areas where the model first-guess is rather accurate and the relative information content of the satellite radiance data is lower, the model first-guess should be used in conjunction with the radiance data. For this purpose new variational assimilation methods for radiance data appear promising to extract useful information from the satellite measurements.

For both these lines of development, the workshop demonstrated how a close cooperation and feedback between the satellite and NWP communities can bring about important improvements in the performance of both.

Wind Data

The value of close cooperation between the two communities was again graphically demonstrated in the context of cloud track winds. The bias in these wind estimates at high speeds has been known for some many years. Efforts to alleviate the bias have been aided substantially by the feedback of information between data producer and data user. As new types of satellite methods for estimating surface wind speed and direction become available we may expect that a close interaction between the two communities will again improve the importance of both communities.

New Satellite Observations

A second motivation was for the workshop was to review methods to exploit the novel microwave observations which will become available to operational NWP from instruments such as SSM/T, SSM/I, AMSU-A, and AMSU-B. To keep the scope of the workshop to manageable proportions we had wanted to limit the workshop to systems which will be used operationally in the early 90s. However a key question for all concerned was: Can much be gained from existing or imminent systems by improved retrieval methods, or are we already limited by the vertical resolution of current observing technology? Thus it was necessary to look forward to systems such as AIRS which will fly in the second half of the 90s, and which will have improved vertical resolution. In this context the workshop addressed the critical need for a high spectral resolution infra red sounder in conjunction with passive microwave sounding.

Discussions and Recommendations

The workshop consisted of three days of intensive presentations, followed by a day and a half of discussions, first in working groups and then in a plenary session. The speakers' presentations form the bulk of this report, while the working group discussions are presented here. The working groups were assigned the following areas for consideration:

Current sounding retrieval methods
Assimilation methods for soundings
Effect of planned changes in satellite sounding on NWP
Satellite wind data
Satellite products for analysis and model validation

The working group documents were reviewed by the plenary session.

International Cooperation and Data Exchange

The workshop was imbued with a sense of the challenges and opportunities offered by the improvements in meteorological and satellite technologies. The international NWP and satellite communities need to deepen their understanding of each other's work so as to maximise the benefit to the community of their common efforts. The lively response from both groups at the workshop augurs well for future developments.

A strong recommendation from all the working parties was the need to support the long tradition of free exchange of meteorological observations for the common good. For satellite observations, which increasingly are exchanged in unprocessed or part-processed form, this concept should include the the exchange of necessary data processing software.

Acknowledgements

The host organisations are grateful to the speakers, and to the participants and observers, for their generous contributions to the proceedings and to the discussions. Their views and recommendations will undoubtedly have a positive effect on the science and practice of operational NWP, and on the development of the satellite observing technologies and data processing techniques needed to support operational weather prediction.

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1. CURRENT RETRIEVAL METHODS FOR TOVS/DMSP

1.1 An Intercomparison Study

Recent work on intercomparison of operational and research retrieval systems and conventional meteorological data have identified a number of areas where improvements are possible. Some of these improvements are discussed in section 1.2. In this section we outline a protocol (sections 1.1b - 1.1d) for proposed intercomparison studies of retrieval systems and conventional data sets. The groups involved include NESDIS, GLA, LMD, UKMO, ECMWF, NMC. International coordination will be through ITSC. We hope to complete the exercise by mid-1990.

The intention is

i) to clarify the differences in performance of the retrieval systems in critical parts of the algorithms: the forward calculation, quality control at the calibration and raw radiance stages, the cloud treatment and computation of the clear radiances, and the retrieval verification.

ii) to clarify procedures for the verification of the products of the algorithms against conventional data and model first-guess fields.

iii) to provide recommendations on the treatment of upper air sondes.

There are three stages in the verification: intercomparison of global maps, identification of regions of high meteorological significance, and detailed local studies.

The study period for global processing will be Feb 6/21 1989, for which a complete set of NESDIS radiance data is available for NOAA-10 and NOAA-11. DMSP retrievals can be included in the study if the radiance data can be made available. In addition, model first-guess fields from ECMWF and NMC will be available.

1.1a **Forward problem**

Although no general agreement has yet been reached on retrieval methodology for satellite sounding products, there is a consensus that 'Physical' or Physical Statistical methods show the greatest potential. There is a requirement to be able to calculate radiances accurately from an atmospheric state, certainly to within an error defined by the accuracy that NWP models can predict the measurements. It is well known that the limitations of spectroscopy cause unacceptable errors in such forward calculations and corrections are necessary. However, the value of these corrections and, in particular, their dependence on air mass, latitude etc are not well known quantities. The most reliable method of evaluating the corrections is by match-ups of radiosonde ascents with satellite measurements. This is currently done by various centres and with various complicating factors. For example, the TOVS data may or may not be limb-corrected/cloud-cleared and sonde data may be extrapolated/augmented in different ways. Consequently there is no general agreement on the behaviour of the various forward models used in the satellite data user community.

We recommend, therefore, that one or more data sets should be set-up or made available for an intercomparison of forward model calculations.

We recommend that the BUAN archive currently being compiled by NESDIS set be used to obtain information on global behaviour of forward model errors particularly in the mid- to upper-level channels of TOVS (HIRS 15, 16, 5, 4, 3, 2, 1 and MSU 2, 3, 4). The BUAN archive contains matched pairs of BUAN radiosondes received by NMC for which at least one collocated sounding was observed by NESDIS. Some BUAN ascents have associated rocket sonde ascents and are timed to be coincident with or near satellite overpass. They are also spread evenly over the globe. The BUAN archive dataset will be made available by NESDIS by the end of 1989.

We recommend that the CATHIA data set from CMS Lannion be used to study in detail the forward model errors in lower peaking channels (HIRS 13 ,14, 8, 7, 6, 18, 19, 17 and MSU 2 at Nadir), since the CATHIA data has coincident AVHRR data which can be used to supply the accurate estimate of the SST and also check that no cloud is present. Radiosonde ascents are also near coincident with satellite overpass, but the data is restricted to the local area centered on Lannion France.

Within both recommendations the sonde/rocket ascent should be uniquely augmented/ extrapolated/corrected as necessary.

1.1b Quality control at the calibration and the raw radiance stages

Bad satellite observations, originating either from instrumental problems or from deficiencies in the preprocessing, may severely alter the quality of the retrievals and have been shown to have a big impact on medium range forecasts.

For that reason we strongly recommend that a quality control procedure be activated at the raw radiance stage. Since such procedures are system dependent and cannot be easily unified, we further recommend that each approach be properly described, documented and validated. Resulting raw radiance fields should then be intercompared prior to any further preprocessing.

1.1c Comparison of cloud treatments and clear radiance computation

The variety of approaches that have been developed to process satellite observations for NWP models makes it almost impossible, at least at present, to sort out recommendations for any unified approach. However, all the systems presently in use go through a few key processes like the detection of the presence of clouds or the determination (direct or indirect) of cloud-cleared radiances.

Therefore we recommend intercomparing:

- cloud coverage fields (clear - not clear flags);

- cleared radiance fields from the various systems as well as from the model field through a fast forward model.

For those systems which are based upon a preliminary correction of the viewing angle, we recommend restricting the comparison to nadir viewing only.

1.1d Retrieval verification

As part of the comparison exercise, the retrievals, and the NMC and ECMWF first guesses, should be verified against a well-distributed group of sondes. The variables to be verified are the quantities used in the analysis systems - (thickness 1000/700/500/300/100/50/30/10, and the precipitable water content for 1000/700/500/300) together with a stability index and some integrated quantities such as the 850/300 thickness, and the integrated water vapour.

Such an exercise would provide a good regional overview of the relative performance of the sondes, retrievals and first-guess. This will help form an opinion on whether the current levels of performance are limited by instrument capabilities or retrieval capabilities.

Similar statistics on the operational retrievals for an extended period (in the form of scatter plots as well as summary profiles) would also be valuable in assessing levels of current performance.

1.1e Case studies

Starting from the global scale the participating groups should agree on a few case studies of meteorological interest for detailed intercomparisons on the regional and point-scales.

The case studies should be chosen to illustrate cases where the soundings mainly agree with each other and differ from the first guess (so bringing information to the model) as well as cases where the soundings disagree significantly from each other and from the first-guess.

1.1f **Recommendations on sondes**

1. The tuning statistics for operational satellite retrievals are more regional than global in character, because of the fact that ascents are mostly made at 00Z and 12Z. NOAA-10 is mainly tuned on Chinese and Eastern N America sondes, while NOAA-11 is mainly tuned on European and Western N American ascents. The lack of timely sonde ascents in remote ocean regions (esp. in Southern Hemisphere) severely limits the representation of these regions. We recommend that WMO investigate the possibility of getting a more even temporal distribution of sonde flights over the globe so as to improve the tuning of the retrievals.

2. When the current Sonde Intercomparison exercise is complete we recommend that WMO determine a standard set of sonde corrections which can be used at NWP centres so as to ensure compatibility of different sondes. Such a development would ensure a sensible basis for the tuning of the forward models used for retrievals.

1.2 Short term modifications resulting from recent intercomparisons

1.2a **Short term improvements at NESDIS**

NESDIS will pursue corrective action primarily in response to the problems in sounding products identified during the 88/89 winter.

(i) TOVS

- Include matched pairs of radiosondes and cloudy soundings in the "tuning" procedures to remove excessive bias in TOVS cloudy soundings.

- Introduce 6Z and 18Z sondes in the tuning procedures for improved global meteorological representation for all soundings, and for both satellites.

- Introduce techniques to monitor sounding products by comparing to the NMC 6-hr forecast with appropriate indicators stored on the products data record. The screening parameter is the "Stability Departure" with variable thresholds.

- Investigate the use of HIRS channels 10, 11 and 12 for moisture soundings.

- Complete and document case study results of TOVS sounding products (collected for March 3 and March 7, 1989) to identify further improvements that can be done in the short term.

(ii) DMSP

- Finalize existing method to compute total liquid water (Q) for screening rain contaminated radiances.

- Introduce limb correction to remove discontinuities across scan path and at latitude boundaries (for retrieval and surface correction coefficients).

- Introduce techniques to monitor sounding products by comparing to NMC 6-hr forecast and includes "quality indicators" in products outputs file. These improvements are scheduled to be operational by late 1989.

1.2b Short-term changes in the 3-I system

LMD will pursue corrective action in response to the problems in sounding products identified in the 88/89 study at ECMWF. The major modifications are

- Improvement in the definition of the variance-covariance matrix of the departure of the first-guess from the true solution. In particular, a dependance on viewing angle has been introduced.

- Refinement in the cloud-clearing scheme.

- Improvement in the detection of rain.

- TIGR data base extension.

2. ASSIMILATION METHODS FOR SOUNDINGS

2.1 Interfaces between measurements and assimilation system

The first question to be considered is 'What is the best interface between the satellite measurements and the meteorological assimilation?' There is no unique answer, as the answer depends on the needs and resources of the satellite data user.

2.1a **Global data processing**

Some research centres are studying the use of raw radiances directly in assimilation systems. However even if adequate telecommunications become available, very few users will be able to undertake the global processing of these data. Therefore there will be a continuing need for a main global processing centre for each satellite system (currently NESDIS for the US satellites; in the future EUMETSAT will have similar responsibilities). These centres are a vital component of the total instrument system.

The satellite global processing centres (NESDIS or EUMETSAT) should have close links with an operational NWP centre. The short period forecast should be used in quality control, validation, and relative calibration (e.g. across an orbit) of the observations.

The satellite global processing centres should make available a partially processed product doing as much as possible of the instrument-specific processing, while maintaining the useful information in a form closely related to what was observed. (Clear column radiances are a current example of this). As discussed in section 3, a forward model and its adjoint are needed to use the information in this form. The centre which has done the processing should provide this model. The quality control and validation done on the data must be considered with the forward model.

The global processing centres should also provide a fully processed product of meteorological parameters. This processing requires assumptions and additional information. There is no consensus on the best way of providing this to suit all users; in particular on whether a forecast should be used. Research and development of both alternatives should be continued. Whatever method is used, details should be made available to the data users, so they can allow for the consequences of the processing when analysing the data.

As well as absolute goals for product accuracy (as measured by "ground truth" observations), the observation processing centre should have a goal of providing data that will improve NWP forecasts. It should work closely with the NWP centre with which it has links to achieve and demonstrate this improvement.

2.1b **Interfaces for local data processing**

In high resolution (mesoscale) NWP systems for limited area short range forecasting, the timeliness of the satellite data is of crucial importance; hence the need for direct read-out stations. A typical requirement is data cut-off times of the order 2 to 2½ hours; this time should include basic data processing such as decoding, navigation and calibration. To achieve this the user has to do local processing. Software packages for this basic processing to level 1.5 ought ideally to be made available by the provider of the hardware system and be looked upon as an integral part of the system.

Software packages for the further processing of satellite data to geophysical quantities, i.e. to level 2 meteorological data, are needed, to support regional applications of the satellite soundings. Financial support for the maintenance and development of such software needs to be provided through an international coordination of space and meteorological agencies.

The free availability of TOVS processing packages has already been of great benefit to local modellers. The required speed of processing poses limits on the complexity of the algorithms, given that the processing is done locally and computer budgets are limited. Envisaged systems with ultra high resolution (spectrally, horizontally or in time) are of obvious interest for regional mesoscale NWP systems, though the greatly increased data amounts pose new problems. The possibility of data processing and/or compaction onboard the spacecraft should therefore be considered.

2.2 Variational assimilation - optimum interpolation

As described at the workshop variational methods are now under development for both retrievals and analyses. In these retrievals, one seeks small changes to a background or apriori estimate of the profile to better fit observed radiances. For this purpose a forward radiative transfer model, its adjoint and a minimization algorithm are used. Nonlinear effects may be included in the forward model. Such retrievals may be considered the vertical component of a more complete analysis.

Four-dimensional variational analyses were also discussed at the workshop. In this approach one seeks small changes to an initial estimate of the model variables at the start of the analysis period to better fit all observations within the analysis period. In the future, by combining these two approaches, radiances may be used directly as data by the four-dimensional analysis.

A variational analysis requires four extra pieces of code, in order to use the satellite data directly:

a) Interpolation/extrapolation from the NWP systems parameters to a standard interface of parameters needed for radiative calculations;

b) A direct radiative transfer model computing the radiances from the forecast model variables;

c) The adjoint of the same radiative transfer model to perform the gradient computation.

d) The adjoint of the interpolation.

The development of a forward model requires the involvement of experts on the instruments and experts from the various main satellite processing and research centres. Several forward models for the TOVS system exist. It is desirable to standardise the interfaces between forward models and assimilation systems, so that the inputs and outputs of each forward model are clearly defined. A proposal for such an interface has been prepared at ECMWF.

Currently, with the retrievals performed separately from the analyses, it is important that the retrieval scheme provide the background which was used to produce the retrieval and a reliable estimate of the statistical properties of the retrieval error. When the forecast is used as the background, the retrieval error becomes correlated with the forecast error. Estimates of these correlations should be produced by the retrieval and allowance for their use should be made in the analysis.

2.3 Studies of the impact of satellite data in numerical weather prediction

The assessment of both new and existing data sources in NWP can be performed using Observing System Simulation Experiments (OSSE) and Observing System Experiments (OSE). OSSE's provide a useful means to examine the potential impact of new data sources, although such experiments tend to give optimistic assessments of the impacts of new data sources in an NWP system as a result of approximating the measurement error. Such experiments may be used to estimate the true potential of existing systems if the retrieval procedures were ideal. With that caveat, OSSE's do offer an important source of information both to the designers of potential measurement systems and to those who are responsible for the maintenance and development of NWP systems. In addition, OSSE's provide contexts for the fruitful collaboration between the measurement and modeling/analysis communities. OSE's are needed to examine the actual impact of a new observing system; they are important complements to OSSE's.

So far, there have been a number of satellite data impact studies, or OSEs. The results have been very conclusive for the Southern Hemisphere, where there is a concensus that the forecast skill has been improved by at least 2 days throught the use of satellite data, especially temperature soundings.

In the Northern Hemisphere, results have been mixed, mainly because of the availability of other data and improved forecast accuracy. The improvement in models has been achieved mainly through increasing resolution and in better analysis/assimilation techniques which extract more information from available data. Satellite soundings suffer through lack of vertical resolution and by giving only height (mass) information from which wind information is derived implicitly.

<u>The failure to achieve the consistent positive impact on operational NWP in the Northern Hemisphere that theoretical and simulation studies lead us to expect, justifies increased effort in R&D of operational processing and assimilation.</u> The impact studies have highlighted potentially profitable areas for this, in particular quality control and the use of mesoscale information.

Data assimilation and forecast impact studies raise many questions on how best to use satellite data in a meteorological assimilation. The result of the forecast studies are probably very sensitive to these technical aspects. Areas of concern include:

- The First guess for the Retrieval

The question of first guess selection for the retrievals needs to be examined in detail. Use of a model prediction as first-guess should be compared to the use of a first-guess derived from a synthetic library through a classification scheme. Each of these approaches has advantages and drawbacks which need to be assessed through controlled data assimilation and forecast experiments.

- Interfaces for Satellite Data and the Assimilation Systems

Satellite data can have many interfaces with an assimilation system. There is no well-established methodology for optimising the choice of interface. For a self-contained retrieval procedure there are many possibilities for the choice of retrieved variables and their vertical distribution. There is a need for further work to clarify the relative information content of retrieval and model so as to optimise the interface.

- Variance - Covariance Matrices

The response of analysis systems to satellite and other observational data is controlled by the variance/covariance matrices of observation and forecast error. Several methods are available to estimate the relevant matrices for satellite data, both from within the sounding algorithm and from verifications against independent data. Investigations are needed to determine if the different estimates of the matrices are mutually consistent, and to resolve any inconsistencies. Particular attention needs to be given to air-mass dependence, look-angle dependence etc.

When progress has been made in this R&D, more impact studies should be performed. They could be made in coordination between several centres whenever it is possible (as was done in Europe, for the February 87 period, from satellite data provided by NESDIS). The cross-checks of the results by different NWP centres has been valuable.

It is difficult to get a statistically significant signal from impact studies, so they should be designed in such a way as to improve the signal-to-noise ratio of the problem. For example, rather than looking at a few forecasts from two parallel assimilations with and without satellite data, more emphasis should be placed on the assimilations themselves. The study of the impact of satellite data on the quality of the short period forecasts used as first guess, especially in critical regions such as the west coast of Europe and North America, should greatly improve the sampling problem.

Case studies for situations where satellite data are expected to be valuable, locally as well as globally, should also be suggested.

3. IMPLICATIONS FOR NWP OF PLANNED AND PROPOSED CHANGES IN SATELLITE SOUNDING FOR THE NEXT DECADE

This group considered planned and proposed changes in satellite sounding instruments from the present to about 2000 and discussed the implications of these changes for NWP. It considered deficiencies of present instruments in meeting the requirements of NWP for global observations of high quality and discussed problems which are likely to arise during the transitions to new systems.

The discussion is mainly concerned with the requirements of NWP; it is recognised that there are other scientific communities with different requirements for these data.

3.1 Expected changes in instrumentation

Expected changes in sounding instruments are summarized in Table 1.

a) NOAA series

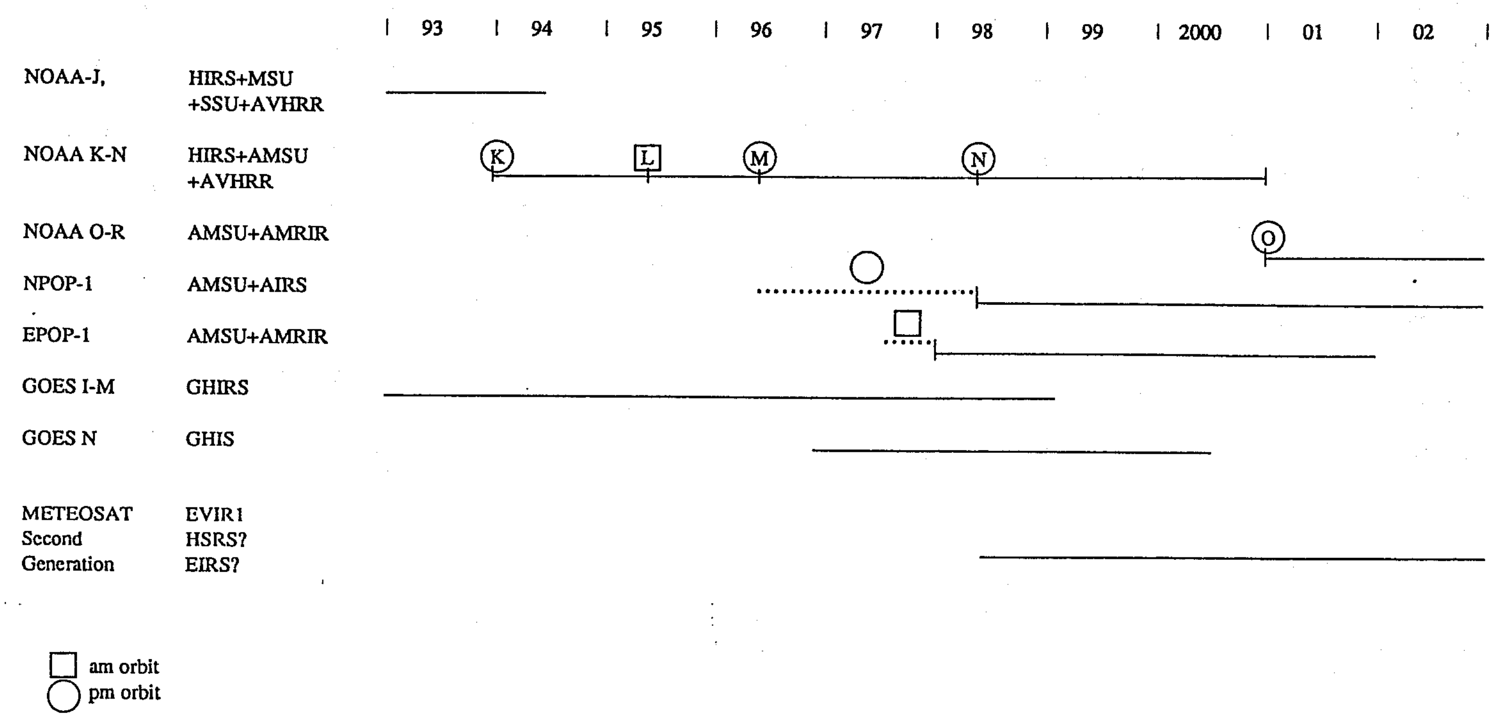
On the present NOAA series of polar-orbiting satellites, soundings are provided by HIRS, MSU and SSU, supported by AVHRR. The present NOAA schedule foresees the launch of NOAA-K, the first satellite of the new series carrying HIRS, AMSU-A, -B and AVHRR in December 1993 in an afternoon orbit.

Planned launch dates for NOAA-L (the last one in the morning orbit) and NOAA-M (afternoon orbit) are April 1995 and July 1996 respectively. NOAA is requesting fundings to procure a fourth satellite of the same series, NOAA-N, with the same payload in afternoon orbit for launch in July 1998.

A new generation of NOAA polar-orbiters is now proposed, from NOAA-O to NOAA-R, with a first launch 2001. The sounding mission of this new series would be undertaken by AMSU(-A, -B and -C) supported by AMRIR, a new multi-channel imager with 3 channels sounding the lower part of the payload. These satellites would provide the primary data source for the operational meteorological community, but NOAA intends to exploit data available from the NASA polar platforms, and in particular AIRS (an instrument of high spectral resolution) to be flown simultaneously with AMSU on NPOP-1 in the 1996-1998 time-frame. It is NOAA's intention to exploit AIRS, and/or instruments of similar spectral resolution, on an operational basis as soon as demonstrated.

b) POLAR PLATFORMS

NASA/NPOP-1 (in an afternoon orbit) would be used by NOAA to demonstrate the capabilities of potential future operational instruments such as AIRS. Data from a


93
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2000
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NOAA-J, HIRS+MSU +SSU+AVHRR
NOAA K-N HIRS+AMSU +AVHRR
K
L
M
N
NOAA O-R AMSU+AMRIR
O
NPOP-1 AMSU+AIRS
EPOP-1 AMSU+AMRIR
GOES I-M GHIRS
GOES N GHIS
METEOSAT Second Generation EVIR1 HSRS? EIRS?
am orbit
pm orbit

TABLE 1

scatterometer, an ERBE-type instrument and other instruments would be made available on an operational basis to NOAA and possibly to EUMETSAT.

The European Platform ESA/EPOP-1 (in a morning orbit) is planned to carry the full meteorological payload including AMSU and AMRIR from 1997/1998. EUMETSAT is now considering options to ensure continuity after EPOP-1.

The Japanese Polar Platform JPOP-1, to be launched in 1999, will not carry a meteorological operational payload, but could be the first one to fly LAWS.

c) <u>DMSP</u>

DMSP polar orbiting satellites are currently providing SSM/T temperature sounding data to the operational meteorological community. In the near future this will be supplemented with SSM/T-2 moisture sounding data. It is expected that NESDIS will process these sounding data and make the product available to users. There is however no provision for either direct readout or visible/infra-red (OLS) and microwave (SSM/I) imagery data for this community within the next decade.

d) Geostationary satellites

At the present time, the only meteorological satellite with sounding capabilities is GOES, which carries the VAS radiometer. From 1991 on, the GOES series will fly new HIRS-like instrument, "GHIRS".

Present plans are to replace GHIRS by a spectral resolution interferometer (GHIS) on GOES-N, to be launched in the 1998 time-frame.

Meteosat Second Generation (MSG) studies are ongoing. Several options include sounding capabilities and decisions are expected on the basis of studies to be completed in 1990. The imaging mission remains the priority for MSG.

3.2 <u>Implications for NWP</u>

a) Requirements

NWP systems have now reached the stage where both the vertical and horizontal resolutions are greater than that of the current satellite sounding products. Present studies are now showing that any increase in forecast accuracy will be limited by observational data. To contribute significantly to short-range forecast accuracy in data-dense areas, satellite data are required of increased resolution, particularly in the vertical but also in the horizontal.

The current use of two polar satellites is important for medium and short range forecasting. This enables global coverage every six hours and ensures reasonable backup in case of satellite failure. Satellite radiance data should be available to NWP centres no more than two hours after observation and retrieval products no more than one hour later.

The form in which satellite sounding data will be required will vary from one NWP system to another. It is envisaged that all NWP systems will require of the data some amount of preprocessing and also require a forward model and in some cases its adjoint, together with statistics and quality control information. However, it is still important for some users to receive some fully processed products. All users will require that the calibration, navigation, pre-processing, etc., of the data from each instrument be carefully and completely described (and updated) by the satellite provider; only in this way will high-quality radiances and products be possible.

b) **The potential utility of satellite sounding**

The potential utility of satellite soundings for NWP is limited ultimately by the information content of the radiance measurements. Limitations in relation to the requirements discussed above are imposed in practice by two basic aspects of atmospheric remote sensing: the effects of cloud and the problem of vertical resolution.

The advent of AMSU, with improved horizontal resolution and additional spectral information, should make a major contribution to alleviating the effects of cloud, and significant improvements in sounding quality in cloudy areas are expected as a result. However, ATOVS (AMSU + HIRS) will only improve significantly (compared with TOVS) on the vertical resolution of the temperature profile in the stratosphere (and below overcast cloud in the troposphere). In the troposphere, infra-red sounders offer vertical resolution superior to microwave sounders, and it is important that combined infra-red/microwave systems are maintained. The possibility of HIRS being replaced by AMRIR is regarded with some concern. Certainly AMSU + AMRIR is preferable to AMSU only, and the high horizontal resolution of AMRIR offers the prospect of improved performance in some partially cloudy areas. However in terms of vertical resolution it represents a degradation compared to HIRS. For temperature sounding purposes an AMSU/HIRS combination would offer superior results to an AMSU/AMRIR combination.

The only feasible option for improving vertical resolution within the next decade is through infra-red sounding at much higher spectral resolution. Improvements in vertical resolution by factors of 2 to 3 are theoretically possible and, if obtained in practice, would approach the requirements of present NWP models in this respect. Therefore the prospects of AIRS and/or similar instruments on both polar and geostationary satellites towards the end of the next decade are strongly supported, as these instruments address one of the greatest weaknesses of current systems.

c) **Exploiting the potential of the data**

Experience with TOVS has demonstrated that the information present in theory is not effectively extracted in practice; considerable effort is required in research and development and operational monitoring and tuning if we are to come close to exploiting the true potential of the data particularly in NWP. Each change in instruments will raise new problems for operational users, and an increased commitment to and resourcing of this area will be essential if the investment in new instruments is to be realised in terms of NWP impact.

Preparations for ATOVS (AMSU + HIRS) are already well underway. NESDIS has plans for a new system for processing and distributing ATOVS data which includes many improvements in relation to the current operational system. Discussions are already well advanced to ensure global data in the form of level 1B data (calibrated radiances), cloud-cleared radiances and retrieved products are distributed to major European NWP centres (at least) in a timely fashion. It is also planned to retain direct read-out facilities for ATOVS data. Thus appropriate plans for distribution of the data are well in hand. However more attention should be paid to the scientific exploitation of the data in the context of NWP. As preparation for ATOVS, future developments and experiments with TOVS will play a major role. In addition, attention is required to the special problems of AMSU not previously encountered: the effects of microwave emissivity and its variation with frequency, and the effects of cloud and precipitation particularly at 89 GHz and above.

For instruments beyond AMSU, it may not be practicable to distribute raw data, pre-processed radiances and products to all major users. New instruments with very high spectral and/or spatial resolution will lead to greatly increased data volumes and may also require new specialised skills of interpretation. Studies are required to develop the most appropriate interface between the satellite centres and the NWP centres for these new types of data. In addition, simulation studies to demonstrate the expected impact of these data on NWP systems would be useful in order to justify the instrument investment that would be required.

In general, for all new proposals for sounding systems, it will be important to involve the NWP community at an early stage to ensure that the designs of the systems reflect the needs of NWP.

d) Compatibility and complementarity

It is important that sounding systems be compatible with each other as far as possible. It is clear, for example, that every effort should be made to keep identical instruments and compatible data systems on US and European polar satellites.

Geostationary satellites have significantly different characteristics and constraints from polar satellites, and their meteorological missions, although they do overlap, are very different in many respects. It is therefore important that the sounding instruments on geostationary satellites, although different, are complementary to the polar satellites in the meteorological problems which they address; the geostationary systems should address primarily the needs of mesoscale forecasting and nowcasting. (We do not address here their important contribution to providing global winds on a synoptic scale). Commonality of instruments and data systems between geostationary satellites should be sought.

e) Continuity

An important consideration for any operational application system, including NWP, is that of continuity of data. It is important to avoid gaps in programmes or indeed high probabilities of operational gaps though premature failures. A continued system of at least 2 satellites is essential to reduce the chance of this occurring. It is also important to avoid frequent changes in instruments; even if these represent improvements in the potential quality of the data, it is unlikely to be exploited.

Although we would like to see HIRS superceded by an instrument of high spectral resolution instrument as soon as possible, it would be advantageous if HIRS could be maintained until this time and preferably with some overlap. We note that the operational requirement for continuity is also consistent with the needs of climate research for long, uninterrupted data sets, and in this respect the continuation of the HIRS series would be very valuable.

3.3 Recommendations and conclusions

- AMSU is expected to make significant contributions to soundings through its improved horizontal resolution, additional information in cloud-covered areas, increased vertical resolution in the stratosphere, and increased information on water vapour and cloud.

- The basic limitation of current satellite sounding data for NWP is their inherently poor vertical resolution. The programmes for implementing infra-red sounders of high spectral resolution (as well as broad spectral coverage) should be accelerated using existing technology where possible.

- The NWP community should be involved in studies of the definition of proposed sounders and their processing systems. Simulation studies should be conducted to assess the expected impact on NWP systems of data from planned and proposed sounders.

- The NWP community will require early and real-time access to data from new systems if they are to be exploited effectively.

- Studies are required to define the most appropriate interface between data from new sounding systems and NWP.

- The requirements for compatible and complementary satellite systems and for continuity of programmes are stressed. Continuity of a polar system composed of at least one "morning" and one "afternoon" satellite is essential.

- Direct read-out facilities should be maintained for future operational sounding systems.

- In order to tackle effectively the crucial problem of making effective use of satellite sounding data in NWP, increased effort and resources will be required during the coming decade.

4. SATELLITE WIND DATA

INTRODUCTION

Global observations of the atmospheric winds are important for atmospheric and oceanic climatological studies and for operational meteorology. This is especially true at low latitudes where the wind field cannot be inferred from the mass field and upper air soundings from the conventional network are scarce.

Cloud motion winds (CMW) derived from successive images from geostationary satellites play an established role in NWP, although there are still problems with the production and use of such data. Improvements on the producer and user side are required; in particular, it is necessary that producers observe the needs of the data users and the NWP community has to better understand the characteristics of the satellite data.

New technologies will be required for a major jump in quality and quantity of wind retrievals from satellite.

4.1 Impact studies

The increase of analysis and model resolution has led to strong sensitivity of forecast accuracy to the quality of wind data. Impact studies with the most recent ECMWF forecasting system show that CMWs are beneficial to Southern hemisphere analyses and forecasts. CMWs have also been found vital in controlling the tropical data assimilation. In the Northern hemisphere the impact of cloud winds is more ambiguous. The background field has a very low error over a large part of the Northern hemisphere thereby raising the threshold of usefulness of cloud winds. This contributes to the strong variability of the forecast impact of cloud winds in the Northern hemisphere as reported in recent experiments involving just a few forecasts. Large numbers of experiments are needed to get a reliable evaluation. Unfortunately the need to run a large number of cases to obtain statistically significant results from impact studies greatly increases the cost of the impact studies. A further complication is that the results of the impact tests are not only situation dependent but also system dependent. Greater efforts are needed to prove that the assimilation systems are using all data to the fullest extent possible. Until satisfactory methods to validate the assimilation systems are in general use, it will be desirable that impact studies be coordinated at several centres.

Observations which have a significant probability of gross errors require special attention by the analysis quality control. Proper statistical tuning of the rejection limits is absolutely vital for use of CMWs. Ideally, a dynamic (situation dependent) quality control procedure should be implemented. Investigations into the error characteristics of different observing systems and the six hour forecast should be given high priority.

CMWs are used in analysis schemes as spot values. This approach will probably enhance the mismatch between observations and the background field as resolution increases and might have a detrimental impact on the forecast. Knowledge of the representativeness and error characteristics is necessary for proper use of satellite winds.

Improved data coverage, e.g. water vapour winds, and more reliable height assignment should improve the information content of satellite winds relative to the background field, especially in the Northern hemisphere.

4.2 Current problems

Most of the operational cloud motion winds (CMW) are of acceptable quality for NWP, however, a small fraction of CMWs is not up to the standard required by the present generation of NWP models. The shortcomings appear to be related to specific synoptic situations with large wind speeds when CMWs can severely underestimate the true wind. Satellite wind producers see scope for improvements in particular in the area of height assignment of a wind vector and also in the horizontal allocation. The problem becomes increasingly stringent as NWP models go to better spatial resolution.

In addition a better quality control of satellite winds is required at the production centres. Internal quality control at the production level should exploit the optical and structural characteristics of clouds. A second step of automatic quality control should use forecast wind fields for screening the satellite winds. Efforts should be made to make the most recent forecast available. Ideally the forecast should be not more than 12 hours old and it should be made available at the highest resolution possible. Manual editing and flagging still remain indispensible as the last step in quality control. Forecast wind fields could also be used at the production level with an optimum interpolation analysis, although there is a danger that a bias will be introduced.

The geographical coverage can be considerably increased by using other spectral channels than the commonly used IR channels for cloud tracking. Low level cloud tracking can be improved by using visible channels. The feasibility of tracking features in the water vapour channels has been shown by interactive methods; research is required to automate the wind retrieval, though interactive methods will still be important.

4.3 New technologies

It is recognized that new technologies for deriving winds from geostationary satellites will be indispensable for a significant upgrading of wind retrievals. In particular, there is the requirements from the NWP community for a better vertical resolution; tracking of clouds provides mainly single level data. Therefore the implementation of high vertical resolution sounding instruments (e.g. HIS) on future operational geostationary satellites is strongly recommended; it also provides the opportunity for obtaining high vertical resolution wind profiles through the measurement of the displacement of small scale water vapour features.

The DMSP Special Sensor Microwave/Imager (SSM/I) provides ocean surface wind speed (not direction) as an operational product. Wind speeds are produced at a spatial resolution of approximately 50 km. Wind speed determination is affected by water vapour burden and cloud. In extreme cases of heavy liquid water content cloud and/or precipitation, wind speed retrieval is precluded. The operational retrieval algorithm is based on statistical regression and does not require a deterministic wind speed/emissivity model function.

Active microwave instrumentation (scatterometer) aboard ERS-1 will provide surface wind and direction over sea. Looking further ahead laser wind measurements seem to be a promising source of global wind data with potential for significant NWP improvements.

4.4 New approaches - future use of satellite wind data

Future variational analysis systems can make use of unconventional data in a much more direct way. When e.g. only wind direction or wind speed is known, a variational analysis can make use of only one of the two quantities when necessary. Alternatively, different degrees of confidence can be assigned to direction and speed. Producers could supply winds even when they are only confident about one of the quantities provided that appropriate flags are assigned.

The fact that the wind observation is representative of a relatively large area rather than being a spot value can be taken into account. This requires further knowledge by the user of the representativeness and limitations of the winds. The methods of deriving the wind together with a quality flag should be provided.

Estimations of the accuracies of the vertical and horizontal positions will become increasingly necessary as the resolution of the analysis and forecast models increase. For the vertical problem, additional information such as the brightness temperature gives the user the choice of using his own height assignment based on the latest forecast available.

The use of single level data, and in particular near surface winds, is still far from satisfactory. Variational analysis methods, improved boundary layer parametrization together with increased knowledge of the boundary layer error structures should increase the usefulness of new types of wind data.

4.5 User-producer cooperation

Improvements over recent years in the quality of NWP models and data assimilation systems have enabled sophisticated data monitoring tools to be developed. Used in the correct way these tools can provide useful information on the quality of the data entering the analysis. For example, with respect to CMWs, systematic biases can be seen in the observed wind speeds in jet-stream regions. Past experience has shown that the feedback of monitoring information to the data producers can lead to an improvement in the quality of the product.

The communication of information from data producer to data user is also important. Changes in operational practices or techniques, such as using a different method of height assignment, may have an impact on the error structure of the wind observations which could have important consequences on the way in which they should be used in the analysis. In particular a quality flag indicating the degree of confidence in the accuracy of the wind could be used in the data assimilation system. Cloud brightness temperatures could also be used to provide an alternative method of height assignment. The advent of the new BUFR code-form will allow the easy inclusion of these extra parameters.

Regular meetings between all satellite wind producers and NWP users would improve the two-way flow of information.

Satellite wind operators should seek to stimulate further research on wind estimates cloud track winds through the exchange of data and software. Cloud track winds will be a vital source of tropical information throughout the next decade not only for NWP, but also for major components of the world climate research programme such as TOGA, WOCE and GEWEX.

5. NEW SATELLITE PRODUCTS FOR ANALYSIS AND MODEL VALIDATION

We discussed five subjects:

i) Cloud properties and liquid water content
ii) Precipitation rates
iii) Albedo and radiative budget
iv) Surface properties:
   - surface temperature and emissivity
   - soil water content
   - ice and snow cover
v) Ozone

For each of the subjects we report on:

a) the present status of the satellite data and products and their use in the ECMWF model either for assimilation or for validation;

b) the prospects, with special attention to future improvements expected from satellites and to the model needs, especially in terms of time and space scales.

Recommendations were made for each of the subjects. Some of them have a higher priority or a general character and are resumĕd in a final conclusion (5.6).

5.1 Cloud properties

5.1a Cloud properties: status

Present operational cloud products are mainly restricted to cloud coverage at a few height levels. Accuracy assessment is an ongoing effort in ISCCP. There have been algorithms developed to derive cloud optical properties, especially cloud liquid water path, but these methods are presently not in an operational status.

Operational cloud products are not used in the model initialisation presently. There is some model validation being performed with ISCCP data. Currently liquid water is not traced explicitly in the model.

5.1b Cloud properties: prospects

Experimental algorithms are available, applied to either 2-spectral-channel data from geostationary satellites or 5-spectral-channel data from polar orbiting satellites or 7-spectral-channel microwave data on board the DMSP. There is a need to have at least the AVHRR/2 channels also on the geostationary satellites to monitor diurnal variations, as is already planned for METEOSAT Second Generation satellite.

Several models will carry liquid water explicitly and will need data for validation. The model needs information at least four times a day with a horizontal resolution of 50-100 km. Data assimilation and model initialization using liquid water distribution should be investigated.

5.1c **Cloud properties: recommendations**

i) Measured radiances shall be archived to allow for retrospective analysis with new algorithms. This implies that the original counts have been calibrated to radiances and that a navigation with an accuracy of about the pixel size has been performed.

ii) Use of cloud coverage could be strongly pushed forward by introducing an accurate cloud height assignment by using, e.g., the CO_2 ratio method which would require an additional spectral channel at 13.3 µm.

iii) Use of cloud liquid water seems to be a valuable prospect therefore microwave -channels like those of the SSM/I together with an additional channel in the 6-10 GHz range should become operational.

iv) The continuation of the ERBE project is strongly supported to obtain broad band fluxes which can be directly compared to model results.

v) The continuation of the ISCCP is strongly supported to allow for the ongoing validation effort at ECMWF and elsewhere.

5.2 <u>Precipitation</u>

5.2a **Precipitation: status**

SATELLITE PRESENT DATA AND PRODUCTS

The available techniques for precipitation estimates from satellites make use of infra-red (IR), visible (VIS) and microwave (MW) data.

Monthly values of precipitation are currently provided on a global scale for climatological purposes, by means of precipitation indices (Arkin) based on IR measurements from geostationary satellites. ESOC contributes to this project by providing a precipitation index from Meteosat IR data. The algorithms are all based on statistical retrievals. The accuracy of the products is limited due to the indirect relationship of cloud top temperature and precipitation. At smaller time and space scales several studies using IR and VIS data have been performed for estimating precipitation from convective clouds. The results are very dependent on the specific situations for which the techniques are developed.

- SSM/I MW data have been demonstrated to be useful in delineating areas of precipitation.

Although MW measurements are more physically related to the rainfall than IR techniques it is still difficult to derive accurate precipitation estimates and they are not operationally available.

Assimilation

No precipitation data is used in operational assimilation. Experimental studies have been recently carried out using a precipitation index deduced from HIRS data in order to estimate the heating rates. The results encouraged further research.

Model validation

No systematic validation is undertaken, but that situation will be changed as the Global Precipitation Climatology Program of WMO gets underway.

5.2b **Precipitation: prospects**

SATELLITE

New processing:

- The use of combined SSM/I and IR data seems to be a promising way to increase the accuracy of the precipitation estimates.

- A GPCP algorithm intercomparison experiment will take place in 1990 to assess the value and limitations of the different techniques developed for precipitation estimates using IR, VIS and SSM/I data.

New Instruments

- The promising results using MW measurements encourage the development of new instruments to ensure the availability and global coverage of MW data.

- The experimental project TRMM (Tropical Rainfall Measurement Mission) will include a precipitation radar and passive MW instrument and will provide good validation data.

Assimilation

Information is required 4 times/day and on scales of 100 km or less. It is also important to retain information on time and space variability at smaller scales. However, it is possible to make use of precipitation at coarser scales.

Model validation

Satellite products at climatological scales (5 days-1 month) are useful for the validation of the mean precipitation rates of the model.

At meteorological scales the resolution requirements are the same as for the assimilation.

5.2c Precipitation: recommendations

1. To follow the result of rainfall algorithms intercomparison and validation in Global Precipitation Climatology Project and develop algorithms for operational use.

2. To inform the community working on algorithm development of specific requirements of the model specifically for meteorological scales.

3. To use the available climatological indices to validate the mean rainfall of the model.

4. To support the development of MW instruments suitable for precipitation estimates to ensure global coverage from operational satellites.

5. To continue research on the use of precipitation of assimilation schemes.

6. To investigate the relationship between lightning distribution and precipitation.

5.3 Surface shortwave albedo, longwave emissivity, radiation budget

5.3a Radiation: status of NWP models

NWP models generate a three-dimensional distribution of radiative fluxes and heating rates from the prognosed temperature and humidity fields and the diagnosed cloudiness. For these computations, some models (e.g. ECMWF) use only one global annual mean value of the surface longwave emissivity and an annual mean distribution of surface shortwave albedo. An assessment of the sensitivity of some models to a better definition of the surface radiative properties (geographical distribution of longwave emissivity, shortwave albedo defined in 2 spectral intervals 0.25-0.68 μm, 0.68-4.0μm) will be carried out in the near future.

5.3b Prospects for satellite derived products

Satellite measurements could complement the information already available from atlases of surface characteristics by providing a weekly/monthly update of the distribution of surface shortwave albedo on a one degree grid basis. Such a product is presently derived in a research mode from polar-orbiting and geostationary satellite measurements. However, a number of problems (corrections for atmospheric absorption and/or bi-directional properties of the surface reflectance, dependence of longwave emissivity on soil moisture) still hinder the operational retrieval of these surface radiative properties for use in a NWP model on a routine basis.

Validation of the components of the radiation budget at the surface and the top of the atmosphere is important and has to be carried out on different time and space scales (particularly for validation of the diurnal cycle).

Whereas a wealth of satellite data is available for validating the radiation budget at the top of the atmosphere, an assessment of the surface radiation budget derived from satellite measurements has to be performed before any comparisons of this product with model-generated surface radiation budget at the model grid-scale on a daily basis.

5.4 Surface parameters: temeprature, vegetation properties, soil moisture, snow and ice

5.4a Surface parameters: status of satellite data

An important type of satellite product is the estimate of skin temperature derived from TOVS and AVHRR data, after correction of brightness data for atmospheric effects, and use of assumptions on surface emissivity. The thermodynamic surface temperature, which is equivalent to the model surface temperature used to compute surface fluxes, can be derived from the skin temperature by empirical formulae. Such temperature estimates are available from NCAR/JPL and NOAA. Vegetation indices obtained from satellite, the main one being the normalized difference vegetation index (NDVI), do not seem at present usable as model input or for model validation, and cannot replace conventional vegetation maps.

Information on snow and ocean-ice extent is available on a result basis. The use of micro-wave data to infer soil moisture and snow depth is still at a research stage.

Surface parameters: status of NWP models

The variables which describe the surface state in the majority of NWP models currently are thermodyanmic surface temperature, surface soil wetness and snow depth. Their computation makes use of surface characteristics like albedo, varying with respect to snow depth in many models, emissivity (constant and uniform in all models), and vegetation cover. Surface variables remain fixed over the oceans, and thus surface characteristics are completely defined through the analyzed sea-surface temperature which is used to assign sea-ice and corresponding values of albedo and emissivity. Over the continents, model variables evolve interactively with both atmospheric and deep ground variables. At the time being, satellite data are not used to analyse continental surface properties at ECMWF.

An effort is starting to use satellite measurements to validate the diurnal cycle of surface temperature (Surface Radiation Budget project).

5.4b **Surface parameters: prospects**

The models are already using a large number of surface parameters in their parametrization schemes. The first expectation, for improvement comes from the availability of data to analyse these quantities, rather than from further refinement of the parametrization schemes.

The primary need for NWP models is to obtain accurate surface temperature estimates for both analysis and validation purposes (though the best use of such data require one to move from the current OI to 4D assimilation methods). This requires a global map of emissivity and improved algorithms to go from skin temperature to thermodynamic surface temperature, using existing data and comparisons with in-situ measurements.

With respect to vegetation, the aim should be to combine atlas and satellite derived information to produce maps of vegetation types and fractional vegetation cover at a spatial resolution of the order of 1°x1°. Research should also be encouraged to derive physical properties for the soil and vegetation from indices such as NDVI and from micro-wave measurements.

Information on snow and ocean-ice extent should be used as additional input to the model analysis. Soil moisture content and snow depth derived from micro-wave measurements, combined with in-situ observations and budget studies could serve as a basis for model validation studies.

5.4c **Surface parameters: recommendations**

1) Set up global surface IR emissivity maps as an intermediate step for the derivation of surface temperature, and also to be possibly used as model.

2) Make input use of surface temperature derived from satellite for the validation of model diurnal cycle over land.

3) Make use of data on snow line and ocean-ice extent as input for the model.

4) Encourage research on the use of AVHRR and micro-wave data to produce map of vegetation cover and soil moisture.

5.5 Ozone

Ozone is the main absorber of the U.V. solar radiation and contribute to the thermal structure of the atmosphere. In addition, because of its long photochemical lifetime in the lower stratosphere, it is a very good tracer of motions at the tropopause level. Total O_3 column variations are found to be strongly correlated with the evolution of the Ertel Potential Vorticity (EPV) on the 350 K potential surface. Form the displacement of small scale irregularities in the total ozone field "O_3 winds" can also be derived which are consistent with analysed 100 hPa winds.

In consequence, there is an important potential for using O_3 data to improve the analyses and our predictive capabilities in the upper troposphere - lower stratosphere.

5.5a **Ozone: status**

The Total Ozone Mapping Spectrometer on Nimbus 7 (TOMS) provides global daily total ozone column with a resolution of about 100 km and an accuracy of 5%.

Several algorithms have been derived in the US and France to obtain O_3 column measurements the TOVS/HIRS2 radiances. It is now possible to have O_3 determinations during day and night with an accuracy of 10% and a resolution of 35 km. With two satellites in operation, a global O_3 map is obtained every 6 hours.

Vertical O_3 profiles are given by SBUV and SAGE instruments. Their accuracy is better than 10%, the vertical resolution is about 2 km but the horizontal resolution is poor.

At present time O_3 mixing ratios in NWP models are specified according to climatological mean data, regardless of any information on the dynamical state of the upper atmosphere and stratosphere. A few GCMs use interactive O_3 mixing ratio. For instance at the DMN a scheme that calculates the O_3 photochemical production and loss has been derived, and O_3 is treated as a fully interactive variable. the computational cost of this approach is of the order of 7% of the total.

5.5b **Ozone: prospects**

Apart from the continuous research work on the improvement of existing algorithms, more work should be directed towards the operational side of O_3 data in weather prediction systems.

Recent works have shown that the use of elaborated diagnostics like EPV can lead to a better interpretation and validation of model results. A similar approach is conceivable and should be followed in case of the O_3 data.

5.5c **Ozone: Recommendations**

1) All the available measurements should be used to obtain global O_3 fields. At present TOVS/HIRS2 raw radiances and TOMS data can provide total O_3 column determination every 6 hours.

2) To seek for the possibility of introducing O_3 as an interactive variable in the NWP model that have a good vertical resolution in the stratosphere, like the ECMWF model. This implies to develop an analysis scheme to assimilate O_3 data.

3) Due to the degradation of the TOMS instrument, the data stream could stop at any time. There is a critical need to maintain continuous measurements of total O_3. The possibility to obtain O_3 determinations during day and night from a geostationary platform, like for instance METEOSAT2, should be further studied.

5.6 General recommendations

1) The state of the art in numerical weather prediction is such that many new types of satellite data can be exploited. Products such as precipitation wind and surface temperature measurements will be exploited first. In a next step, liquid water content evaluations should also be used.

2) The group recognizes the general lack of standard algorithms and strongly recommends efforts to establish and validate standard algorithms for the conversion of satellite measurements to geophysical quantities.

3) The group recommends further efforts to develop the interactions between satellite observers and modellers. In particular the "model-to-satellite" approach seems particularly appropriate for model validation. In this method one synthesises the fields observed by the satellite from the model prescription, and compares the results with the satellite measurements.