Global weather prediction
-Possible developments in the next decades -

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1. INTRODUCTION
(Some personal remarks)

It is by now almost fifty years since I first read L. F. Richardsons book „Weather prediction by numerical process"(Richardson, 1922) found by a chance stashed away in the library at the meteorological institute in Uppsala, Sweden. As a young student in theoretical physics with a genuine interest and curiosity in weather and weather prediction I found the book all in all exciting, although quite a bit eccentric. The professor at the institute, Tor Bergeron, had a lot of reservations as he did not consider weather prediction by strict mathematical methods as practically possible. Not even the fastest computer could feasibly consider the detailed calculation of clouds, precipitation mechanisms and the full complexity of the radiation calculations. The idea was interesting in theory, he believed, but not useful for weather prediction.

Even if Bergeron's views in retrospective may seem conservative and uninformed, as in fact without my knowledge at the time, the group in Stockholm around Carl-Gustaf Rossby had already in 1954 produced operational numerical forecasts based on the barotropic model. In fact it was even produced in time to be operationally useful, Fig. 1. However, this model was an extreme simplification of the real atmosphere and its practical use in weather prediction was rather limited, so Bergeron´s critical remarks were understandable and justified.

However, I was not discouraged. Another book, somewhat later, which fully open my eyes for the potential of a quantitative approach to weather prediction was Dynamics of Climate published as a report from the proceedings of a conference in Princeton on Application of Numerical Techniques to the Problem of the General Circulation in 1955. (Pfeffer, 1960). In the meantime I had also met members of the Rossby team, Bert Bolin, Bo Döös and Aksel Wiin-Nielsen. All of them meant a lot for my continued interest and motivation to work in meteorology and NWP.

Then in the mid-1970s, when we started the work at ECMWF, the situation had changed significantly. Bergeron, now at the age of 85, seeing the enormous possibilities with Numerical Weather Prediction, NWP, sent me a long enthusiastic letter in long hand, outlining areas of research which should be prioritized. In several respects we actually followed this general advice. I wish he would know what has been accomplished today in 2004.

Looking back now over the last 25 years the evolutionary progress in NWP has continued. Most of what have been implemented were broadly anticipated many years earlier, although few if anyone could have foreseen the enormous development in computing and in satellite based observations. Without that development in technology, todays achievements in NWP would not have been possible. An additional important aspect is that the development has been evolutionary, making it possible for science and technology to proceed stepwise, hand in hand.

In this lecture I will try to outline some ideas for the future and my belief the way operational weather prediction in the medium and longer range may evolve in the next decades. I will try to give a broad outline also involving aspects on the infrastructure of large-scale weather prediction including dissemination and use of such predictions.

2. PREDICTIVE SKILL IN NWP.

Have we reached the limit of skill in deterministic prediction of the synoptic scale and if not yet, how close are we? Following Lorenz seminal study on predictability (Lorenz, 1982), later studies, such as by Simmons and Hollingsworth (2002), have confirmed the principal results of Lorenz, Fig. 2. Two aspects of this result need to be highlighted. First, by comparing the skill of the ECMWF model between 1981 and 2001, the model error growth is slower in 2001 indicating genuine model improvements. Second, the initial error is almost halved, due to improvements in observations and data-assimilation. As discussed by Bengtsson (1999) a more accurate model interacts positively with the data-assimilation. However, considering the predictability estimate as an upper bound on predictive skill and the actual predictive skill as the lower bound, it is clear that potential for further improvements in prediction is rather limited as the two curves in the latest years are not only very close, but also virtually parallel. Further improvement in forecast skill is therefore most likely to come from a further reduction of the initial error. Another interesting result is that predictive skill in the medium range at the Southern Hemisphere are almost as good as for the Northern Hemisphere (Bengtsson, 2001, Simmons and Hollingsworth, 2002), Fig 3. Although these results are from the ECMWF model, similar improvements have taken place at most of the major forecasting centers.

It is not only the forecast skill in general which has improved but also the capability to predict intense weather systems including smaller scale extra-tropical and tropical storms, Fig 4, and Fig. 5.

3. HOW MAY NWP EVOLVE IN THE FUTURE?

Here I will concentrate on the large-scale global and regional aspects of numerical weather prediction. I will also try to address the longer-range aspects of weather prediction thus considering predictions beyond what we may consider as synoptic predictability. I will consider the following four areas:

(i). Modeling, observations and data-assimilation

(ii). Extended prediction

(iii). Computational possibilities

(iv). Communication and provision of forecast information to users

3. 1. MODEL ING AND DATA-ASSIMILATION.

One of the greatest achievements in operational NWP in recent years is ensemble prediction (Palmer, 2001), whereby a series of integrations are undertaken from slightly different initial states or from slightly different model versions, all in principle equally possible, Fig. 6. An ensemble prediction provides not only a measure of the reliability of a forecast, but perhaps even more important, a measure of the risk of extreme events. A key scientific question to determine is the number of cases needed in an ensemble prediction. The selection of initial states should be done in such a way that the largest possible spread is obtained between the different members of the ensemble. The ensemble system at ECMWF consists presently of fifty members. So far in most applications only the initial state has been perturbed, but in some applications the model parameterization has also been perturbed. This makes scientific reason as many parameterization schemes are highly empirical with parameters only approximately known. There exist also several different parameterization schemes such as for convection or turbulence, presumably being equally realistic. It is logical to follow a similar approach as in perturbing the initial state and select such versions of the parameterization which provide the largest spread. As all predictions a priori have limited skill it seems that all weather and climate integrations need to be undertaken in an ensemble mode. The question how to optimize and to limit the size of such ensemble integrations will be a most delicate issue in the future.

Non-hydrostatic models are presently being put into operation and will in some years presumably be replacing models based on the primitive equation. I believe an advantage will be a more direct way to handle parameterization of fast physical processes such as convection and turbulence. Numerical techniques will certainly include higher computational efficiency and accuracy, better conservation properties and more accurate treatment of the transport of passive and semi-passive constituents.

What then about more traditional model improvements such as further increase in resolution? The question of the relation between horizontal and vertical resolution needs to be more comprehensively looked into. Most models today generally have larger vertical truncation errors than horizontal. It is required that models consistently can describe key physical and dynamic processes thereby providing a systematic approach to the handling of organized meteorological weather systems such as tropical and extra-tropical cyclones. A representative resolution for large- scale prediction of the order of 10 km. and a hundred to a few hundred m in the vertical seems reasonable to aim at. Results from limited area predictions seem to support such a resolution. This may not be justified based on available observations but on a more correct treatment of physical processes and non-linear interactions. Needless to say, this will have to be balanced against further developments of numerical schemes and grid representation. Presently, it seems to be a return to finite difference schemes away from the spectral transform models.

Physical parameterization is still being done on an ad hoc basis. Conceptual ideas are being applied on model resolvable scales in spite of the fact that they represent phenomena which are much smaller in scale. An approach to address this could be to use in-built sub grids or to enforce characteristic statistical distribution of sub-grid scale phenomena.

As discussed in section 2 the rate of growth of errors in NWP is rather close to the theoretical limit and additional improvements will require a further reduction in the initial error of the main variables, wind and temperature. Further improvements through better data assimilation are likely, but presumably limited, so the main improvements will occur by more efficient use of present accurate observing systems or through the development of new ones. We believe that such systems must be all weather instruments and preferably be based on direct measurements as passive satellite soundings in the visible and near infrared have severe restrictions. To avoid problems with clouds, efforts should be directed towards use of lower frequencies, such as micro-waves and short frequency radio-waves such as used for GPS. Further work is needed to increase direct measurements from aircraft including vertical profiles at landing and take off. Systematic use of soundings from airplanes (drop sondes) is another interesting possibility. May be there could still be an opening for constant level balloons, which by far are the best possible observational platforms for NWP.

One of the most dynamic areas of research in recent decade has been in data-assimilation. The flow of observations in time and the state of the model is getting more and more integrated as the variational approach has been extended into four dimensions. A main remaining issue in data-assimilation is the integration of dynamic and physical information. This is being highlighted by the increasing use of data obtained via remote sensing from satellite and radar measurements. These observations do generally not observe the main geophysical parameters directly but instead secondary information such as clouds, precipitation and for that matter also water vapor. To directly incorporate such information in data-assimilation is a fundamental challenge, as it will require major efforts and resources. I personally believe that the use of such indirect information is more valuable for model development and validation and less useful for providing initial data. Given an advanced model and accurate wind and temperature profiles, models should increasingly be able to generate physical fluxes and the hydrological cycle.

4DVar data -assimilation make it possible in advance to identify areas from which it is important to obtain observations in order to reduce forecast errors. This is interesting but presumably only applicable for shorter-range predictions. Unfortunately it involves complex logistics and is therefore not likely to become an operational feature, but will be very useful in large-scale field experiments.

The development of coupled models for extended integration will require major efforts by the modeling community. This effort is likely to imply a further integration of climate and weather modeling. Except in a few cases this is long overdue as the climate community would very much benefit from the modeling expertise in NWP and vice versa the NWP would benefit from the know-how in the modeling of slow physical processes and experience in ocean atmosphere coupling.

Longer prediction will of course suffer from limited skill, but I believe many users are exploring ways to use limited skill in combination with ensemble type predictions, which will include warnings for extreme events. Predictions in the extended range (longer than a couple of weeks) will require the incorporation of land surface processes, sea ice and the upper oceans. How long useful predictions can be done is an open question as the quality and the usefulness will vary strongly from area to area. Present results indicate that many tropical areas and some regions in the extra-tropics, such as North America, are more predictable than for example Western Europe. Predictability is also higher in certain periods as in cases with pronounced El Niño events.

3. 2. EXTENDED PREDICTIONS

One of the major achievements in prediction has been the possibility to forecast El Niño events and its influence on weather. This is probably one of the largest accomplishments in prediction during the last decades. There are two main reasons why El Niño is a source of extended predictability. First, the temperature in the eastern tropical Pacific ocean undergoes well defined low frequency variations on a time scale with its peak around 4 years. Second the surface pressure and atmospheric circulation, the Southern Oscillation, are strongly coupled to such SST anomalies, Fig. 7. This circumstance has made it possible to predict El Niño and the associated atmospheric circulation anomaly. In cases of well developed events useful predicted skill is extended about a year ahead, Fig. 8. The predictive skill varies considerably geographically. It is well marked in the tropics and in the Western Hemisphere extra-tropics, but to a very limited degree over Western Europe. Major efforts are under way to improve extended range prediction in general using coupled ocean-atmosphere models, but success so far is limited. Predictability studies suggest that there is scope for considerable improvements although predictive skill is likely to vary from case to case.

As the atmospheric flow over western Europe exhibit marked modes in the circulation between either strong or weak westerlies, the North Atlantic Oscillation, NAO, considerable hopes have been focussed whether the different phases of NAO can be predicted in advance. However, why the atmospheric circulation in the North Pacific is well regulated by ENSO the NAO is essentially dominated by chaotic weather events limiting predictive skill to that of weather systems or at most a few weeks. As there are indications that NAO may be influenced by multi-decadal ocean circulation linked to inter-decadal variations in the tropical Pacific and the Atlantic ocean (Latif, 2001) some predictability on this very long time scales may well exist.

Concerning the overall question of predictability we must note that our predictability assessment is based on model experiments with all its limitation. Reality may behave differently. A simply model could actually indicate less predictability than a more advanced model as can be seen from Fig 9. Predictability of the response to El Niño has been demonstrated to be feasible first when the models are capable to correctly reproduce the phenomena. The ECMWF model was used in the mid 1980s to show that there was no appreciable response to El Niño as a cold and a warm event had very similar atmospheric response. This was incorrect and presumably due to an insufficient convective scheme in the operational model at the time.

3.3. COMPUTATIONAL POSSIBILITIES

There are presently no indications that the relentless increase in computer performance is slowing down. It is therefore not unlikely that we will have computers with performance some 2-3 orders of magnitude more powerful than now and with corresponding increase in storage capacity. This development will probably to a large extent be driven by requirements in consumption goods such as sophisticated cameras, personal computers and toys. This suggest that future supercomputers are likely to be based on huge parallel computer systems as the market for specialized super computers is too narrow. Using off the shelf computers, such systems can be affordable even by less affluent groups as recently demonstrated by the University of Virginia with the Apple G5 super system. With the extended use of ensemble prediction the disadvantage of parallel computer systems will also be less severe.

I anticipate great strides forward in specialized software development. This is an important area in meteorologically education. I expect that simple users oriented graphically based window-type input and output system may come in the future. As I can witness from personal experience it is still overly complicated to run a model in Unix code unless you write computer programs regularly!

3.4. PROVISION OF FORECAST INFORMATION TO USERS

Internet is probably one of the most important developments for the flexible dissemination of meteorological forecasts and different users-derived products from these forecasts. It provides a perfect system for real time dissemination including both information which is freely available and information to special users through password protection. In the near future there will be no restriction at least in principle where such information will be available as high capacity satellite communication will provide Internet connection on any place on Earth. Furthermore, as small portable computers are expected to have supercomputer capacity (Giga to Tera flop) advanced local calculations can be carried out including numerical weather predictions for selected limited areas on the local computer alternatively on the server. However, I expect the cost of computing power to decrease faster than communication cost so it very likely that also advanced calculations will be done more and more on the users own local computer.

It may be interesting to speculate about the relative role of national meteorological services, private companies and the advanced users themselves. Needless to say, the cost for the provision of observations, central prediction services and general infrastructure for communication and distribution need to be covered. As nations have different policies here, problems are likely to evolve. Nevertheless, the overall responsibility for global observations is gradually taken over by the leading nations or alternatively by nations sharing the responsibility and cost as for example in Europe.

Generally, I believe that the central production of numerical forecasts only need to be carried out at a reduced number of places. Even if it make still take some time, I am sure that the European Union, for example, will manage to centralize operational meteorological forecasting in Europe. There is simply no rational reason for the now 25 members of the EU to have fully developed central forecasting capabilities when they already finance a common institute as ECMWF. This would mean that the role of ECMWF would have to be changed by adding some of the operational functions typical of the major meteorological services. This can perhaps also be managed by outsourcing such functions. Special forecasting services can possibly best be handled by the customers themselves or by private forecasting services. The responsibility of the observing systems can equally well be handled by a central agency which for Europe already is the case for satellite information as with EUMETSAT. Such an agency should also take over observational obligations for climate monitoring. Similar arrangements could be implemented in other parts of the world.

Meteorological information including general weather forecasts and weather and environmental warnings should be provided free of charge as a public service. The policy of United States, for example, is here clear with a general free access to forecast information, while the policy in Europe varies between countries, but is in general more restrictive as some meteorological services are partly commercial. For this reason even the forecasts from ECMWF have restricted use and only a minor subset is provided free on Internet. This creates a somewhat peculiar situation and the intelligent user selects of course the forecast products which are free of charge unless the others are of significantly higher quality. This is hardly the case any longer and not likely to be the case in the future. However, major changes in the way operational meteorology is organized are probably unavoidable as it will be driven by the future development in NWP.

First, present NWP are already so detailed, see Fig 10, that no real interpretation is required and users with a minimum knowledge of meteorology can easily read and interpret such forecasts. Already now excellent local meteograms are available on Internet. Fig. 11. As models are becoming more and more advanced such a direct interpretation will be even easier in the future.

Second, modeling and data-assimilation will become more and more complex and highly specialized skill and training will be needed in order to have the capability to undertake such work. It will not be feasible in the long term for traditional meteorological services to hire such experts, and therefore a general centralization of such an activity is the most rational solution. Presently, many smaller institutes have insufficient resources to develop advanced models and data-assimilation systems on their own without access to meteorological software developed at the main centers.

Third, the need to have forecasts from different centers to better assess predictability and risks will gradually go away as the central facilities will produce ensemble forecasts which can estimate risks in a more rational and systematic way.

4. CONCLUDING REMARKS

I have here outlined some possible future avenues in operational NWP including aspects on its dissemination and use. I anticipate that the development of more realistic weather prediction systems will continue. Ensemble prediction is expected to be an essential part of all operational systems on all time scales. Great challenges for the future will be the need to built better data-assimilation systems for coupled models including the incorporation of new observing system being developed.

Further improvements in prediction is expected to be slow as we are likely to be close to the limit of predictive skill. I anticipate more sizeable improvements in extended predictions through more realistic models for the oceans and for land surface processes. However, predictive skill is likely to vary considerably between different areas, different times and for different part of the year. The practical value of such forecasts will be highly improved by ensemble predictions which also will be extended to include perturbations of the forcing functions of the models.

Weather information will continue to globalize and increasingly more information will be provided over Internet. This will also include dissemination of initial data and boundary information to provide possibilities for local predictions for limited areas. It is my hope and expectation that most of this information will be provided free of charge. The high quality of these products will reduce the need for special meteorological interpretations and could be applied more directly by the users.

What will be the future of the national meteorological services? I believe many of the smaller services are likely to be transformed into partly privatized agencies, if at all needed in its present form, having special agreements with the main centers around the world. If the EU will continue to develop for years to come, a natural development for Europe is to make ECMWF, or its successor, to a joint EU meteorological service. Coordination of the observing systems could preferably be done along similar lines. Similar arrangements, where applicable, in other parts of the world, may also evolve.

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FIGURES and CAPTIONS

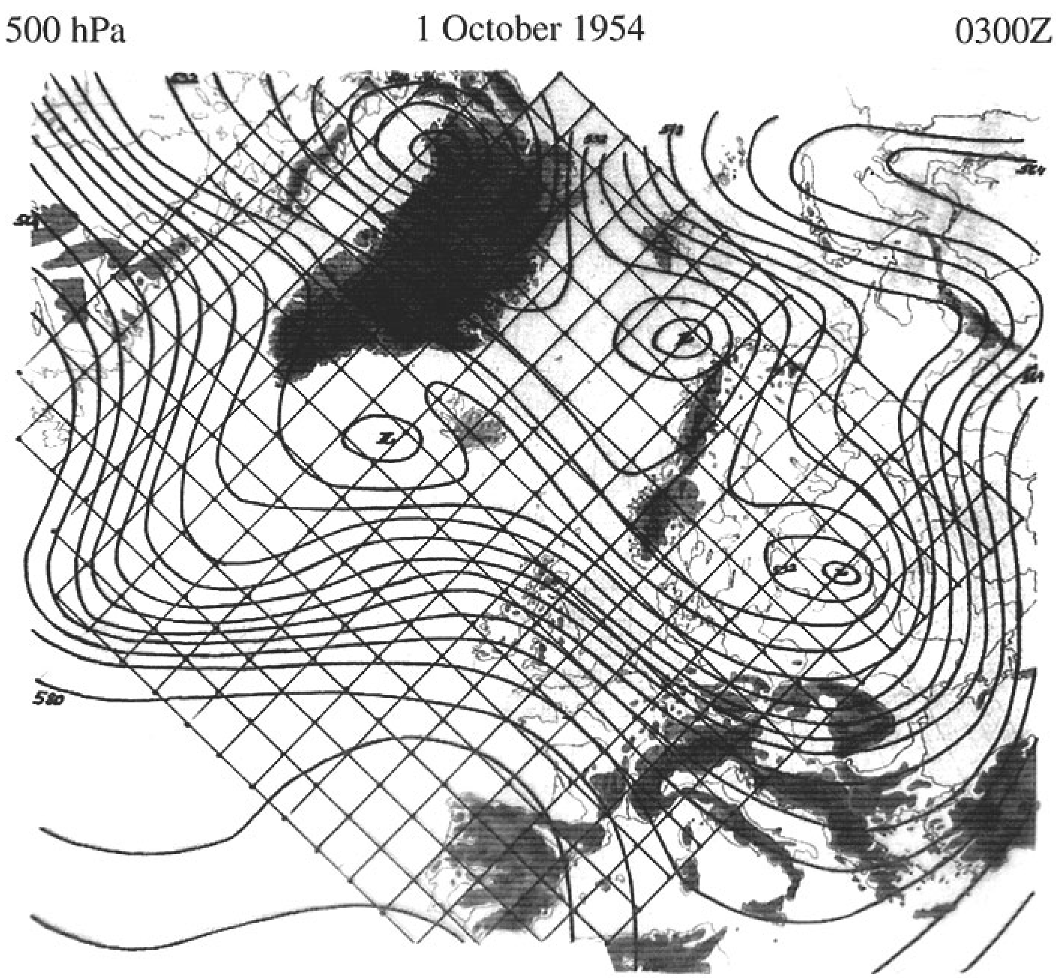

Figure 1. (a) 500 hPa height for 1 October 1954, 0300Z. The field is the initial state for a 72 h barotropic forcast

500 hPa 1 October 1954 0300Z+72hrs.

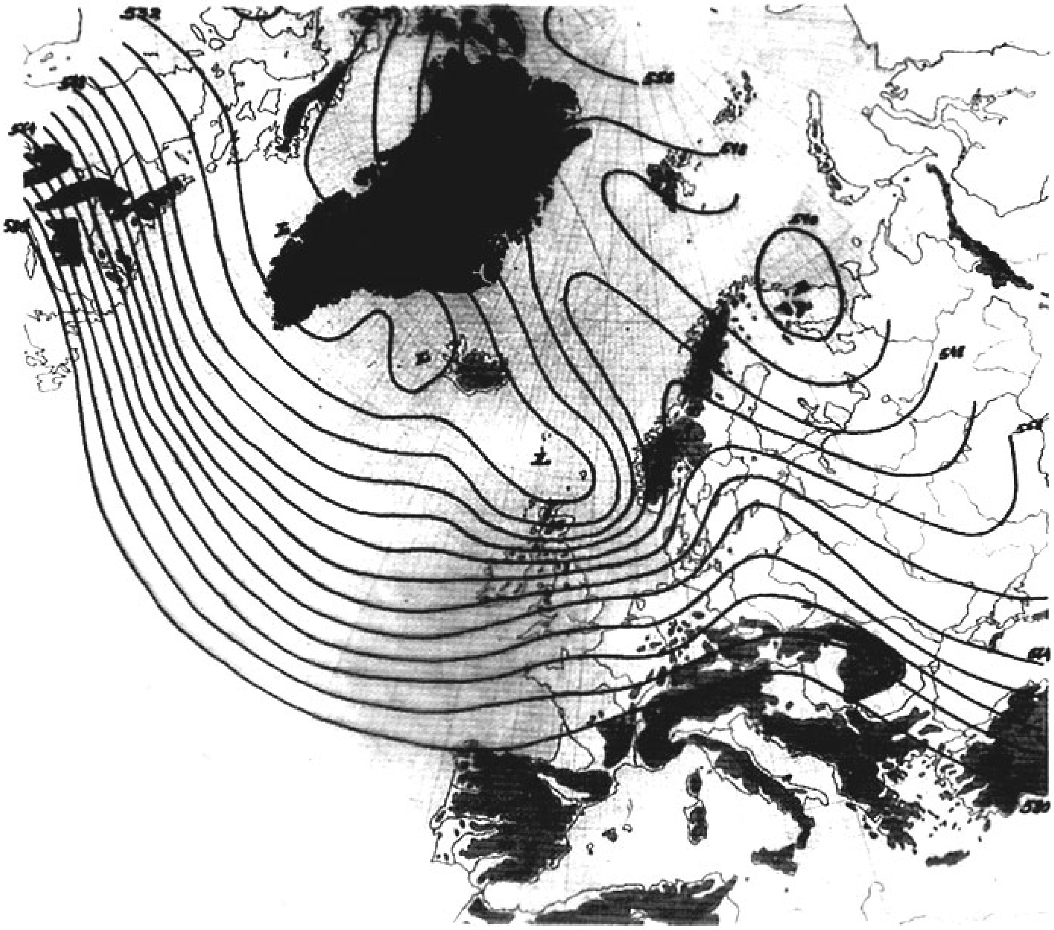

Figure 1. (b) 500 hPa height for a 72 h forecast from 1 October 1954, 0300Z

500 hPa 4 October 1954 0300Z

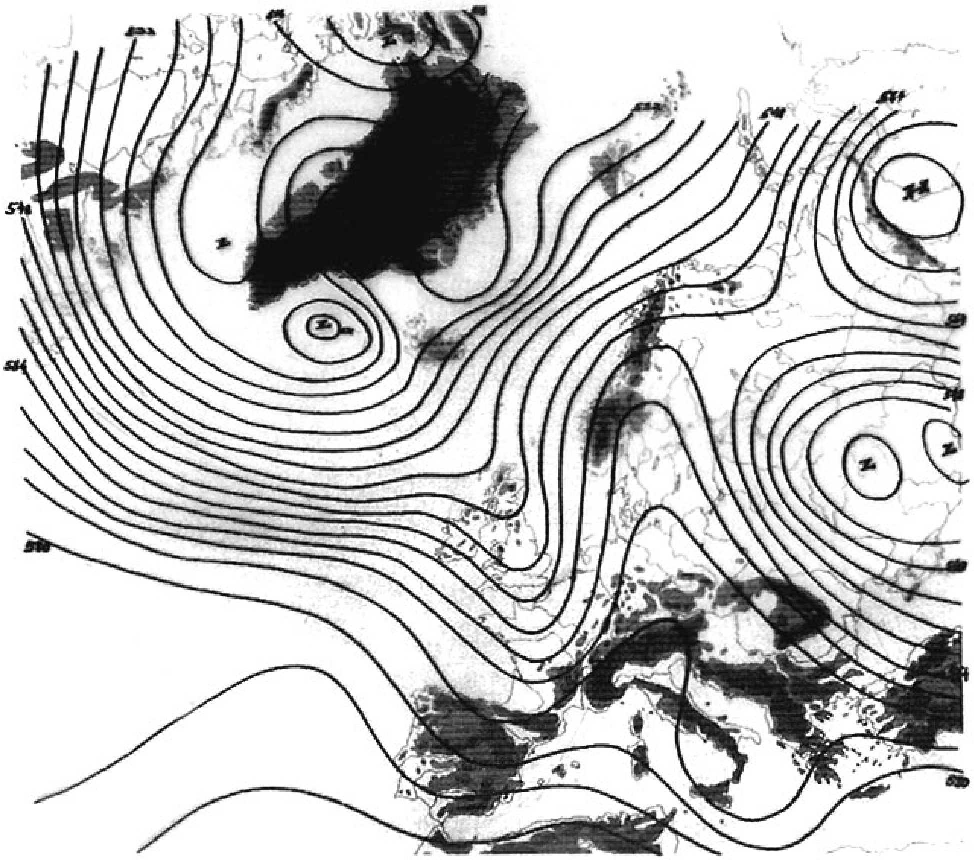

Figure 1. (c) the same as (a) but for 4 October 1954, 0300Z. (From Bengtsson, 1999, Fig 2,3 and 4 therein)

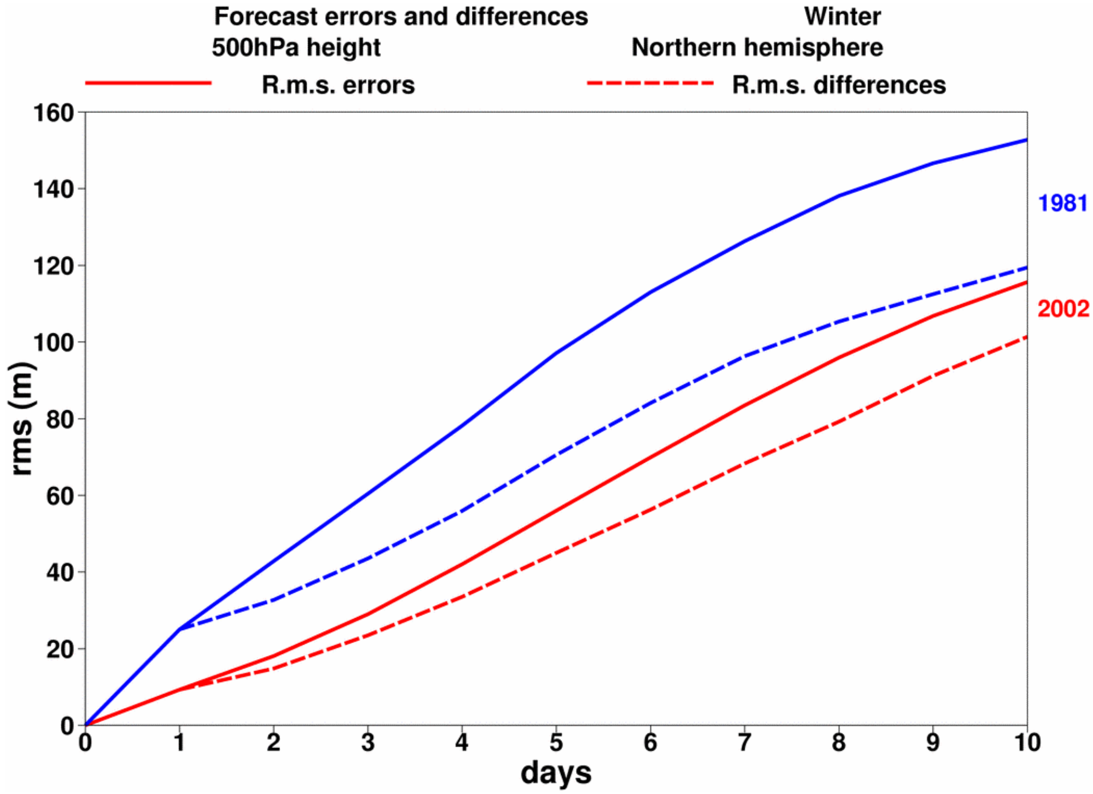

Figure 2. Root-mean-square 500hPa height forecast errors (solid) and differences between successive forecasts verifying at the same time (dashed) as function of the forecast range, computed over the extra-tropical Northern Hemisphere and shown for the winters of 1981 (blue) and 2001 (red). From Simmons and Hollingsworth (2002)

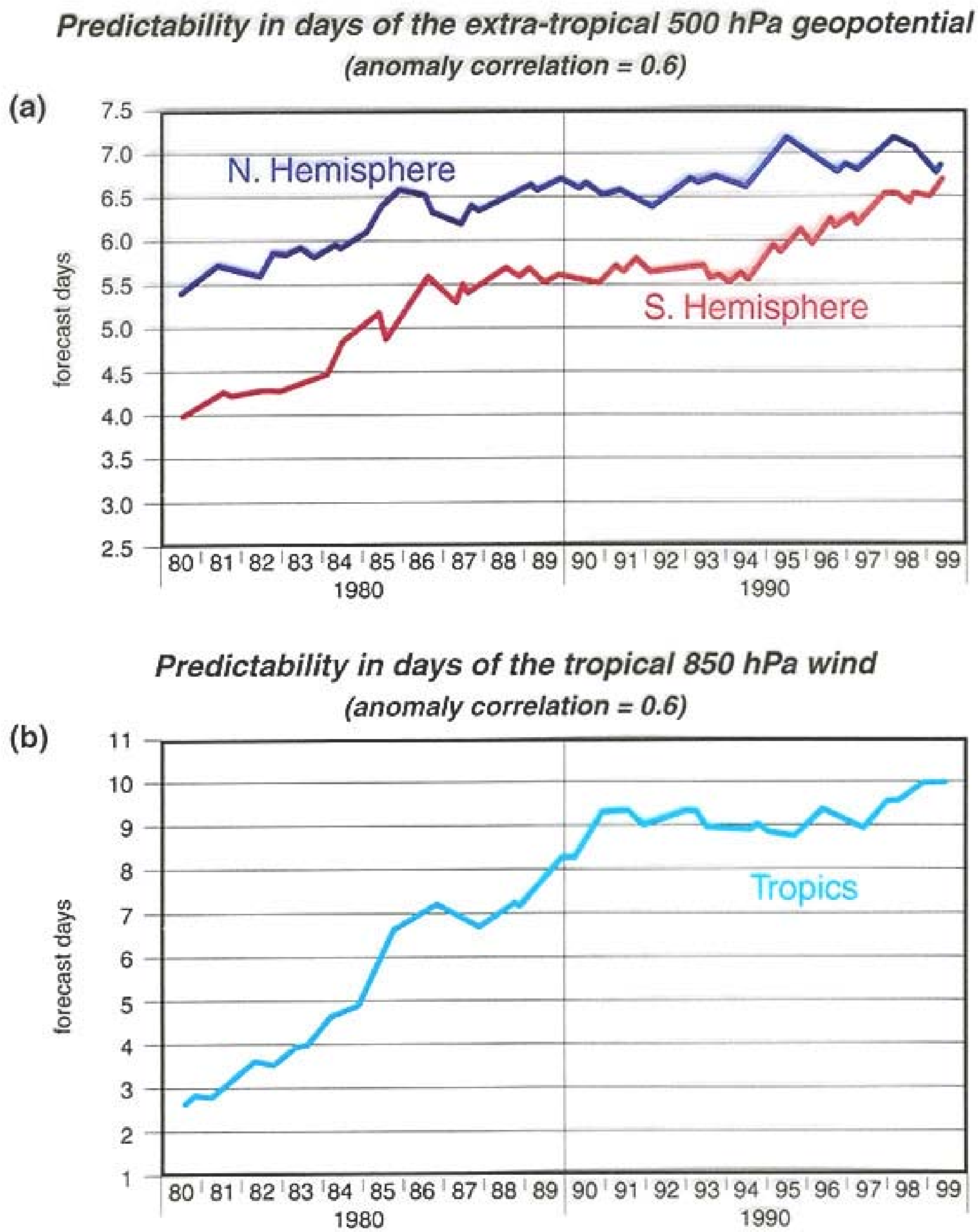

Figure 3. (a) Predictability in days by the ECMWF model of the height at 500 hPa for the extra-tropical Northern and Southern Hemisphere, respectively. (b) The same but for the wind at 850 hPa for the Tropics (from Bengtsson, 2001, Fig 7 therein)

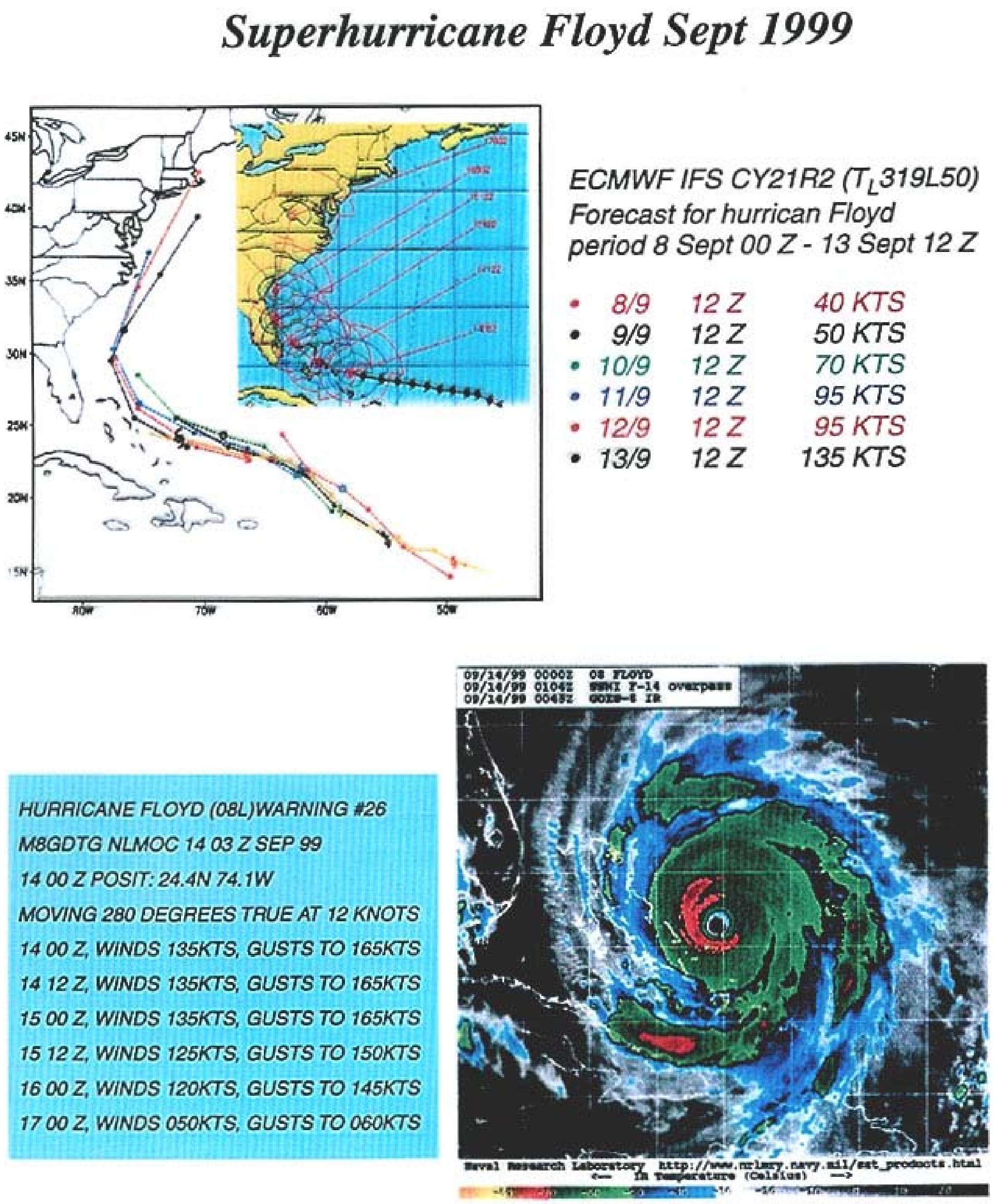

Figure 4. Observations and forecast trajectory of the super-hurricane Floyd in September 1999
(from Bengtsson, 2001, Fig 8 therein)

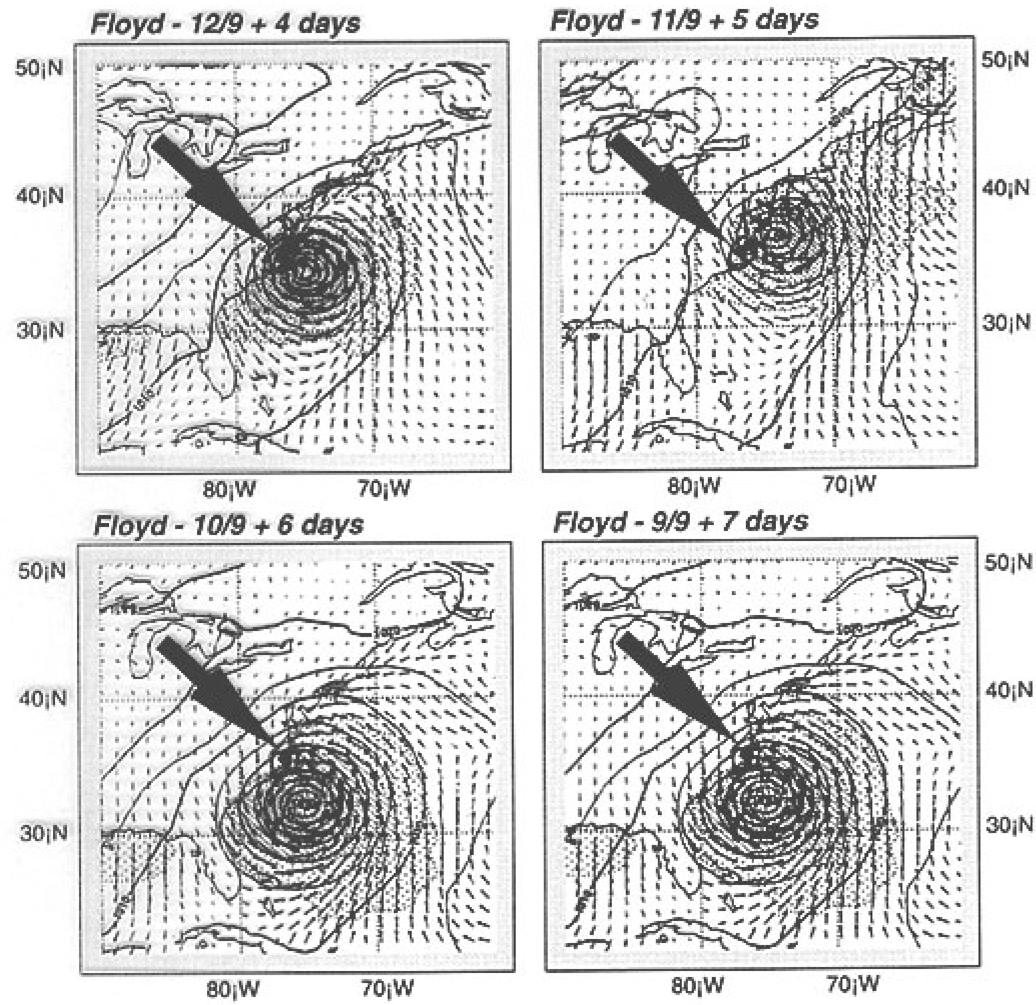

Figure 5. Successive forecasts for day 4,5, 6 and 7 all valid at 16 September 1999. The arrow shows the observed position of the center of the super-hurricane Floyd. (from Bengtsson, 2001, Fig 9 therein)

Predictability of Weather

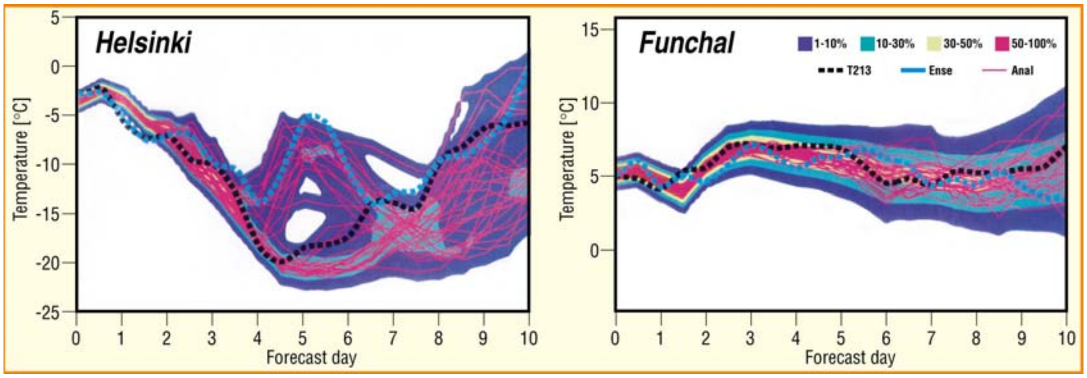

Figure 6. Example of ensemble prediction (Courtesy ECMWF)

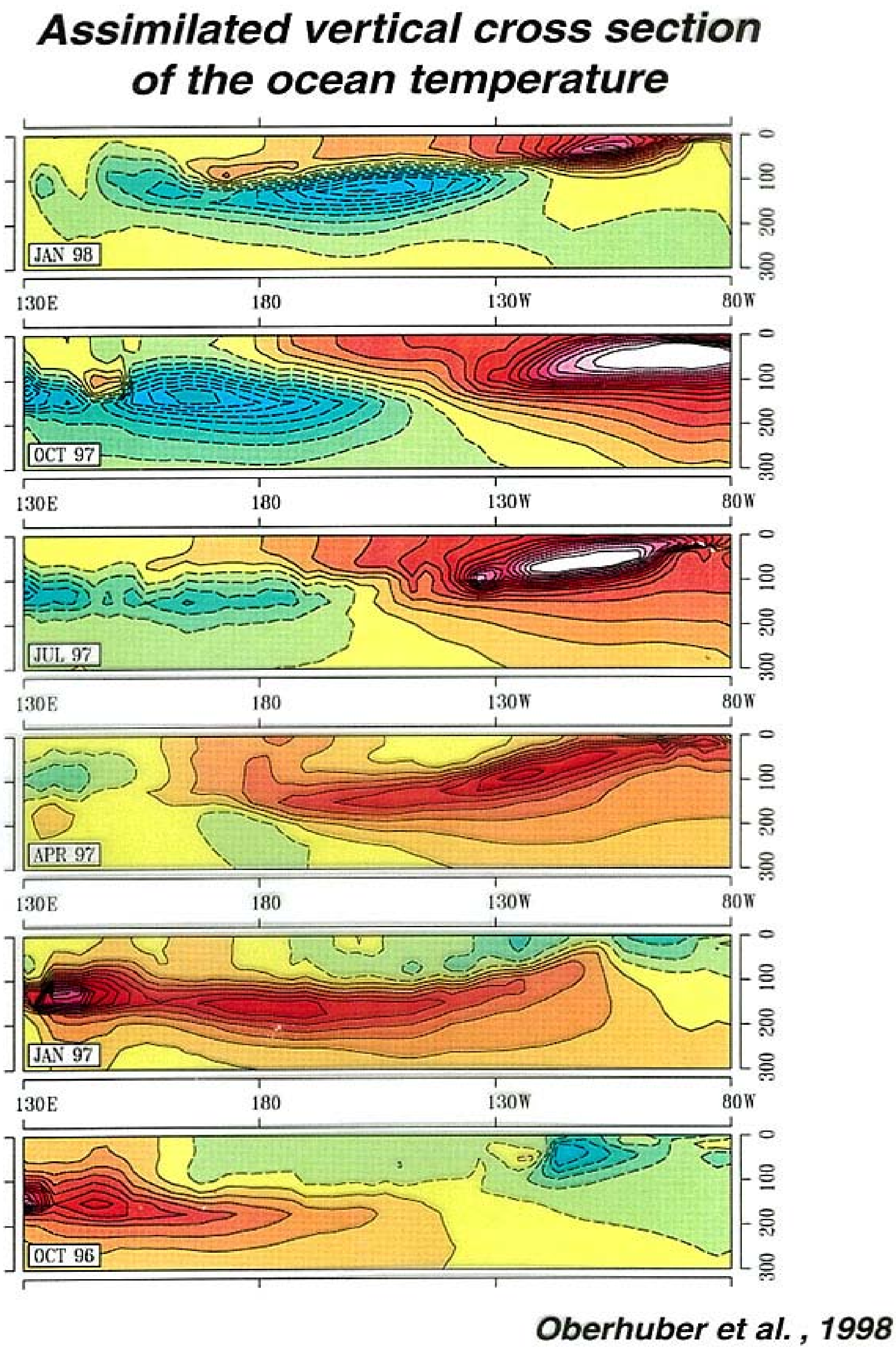

Figure 7. Snapshot of upper ocean temperature anomalies prior, during and after the last major El Niño 1997/98 (from Latif, 2001, Fig 3 therein)

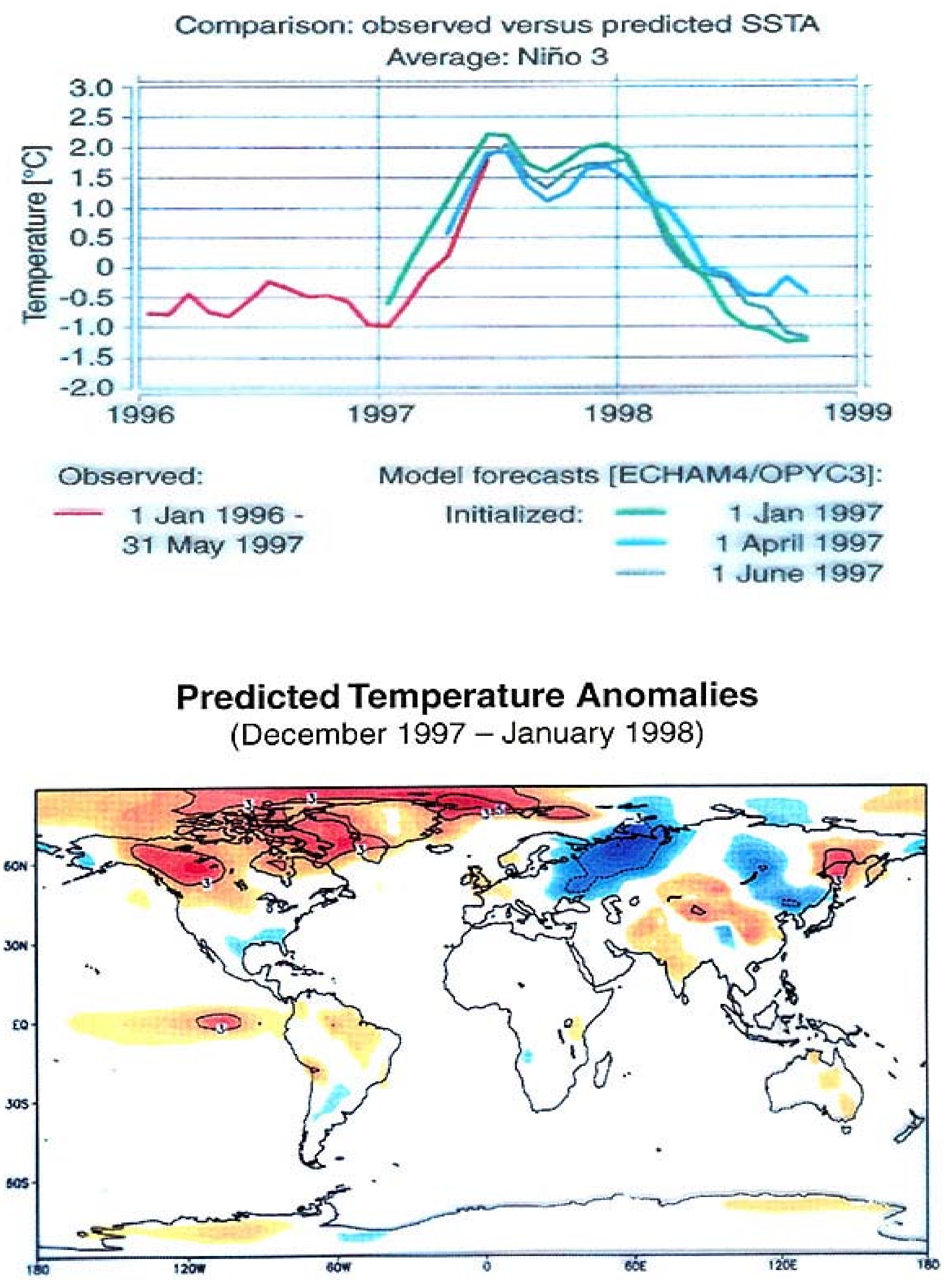

Figure 8. Example of an El Niño forecast with a coupled ocean-atmosphere general circulation model. The coupled model was initialized by driving it with the history of the observed SSTs up to December 1996. The upper panel shows the observed SST anomaly in July 1997, while the lower panel shows the SST anomaly predicted by the coupled model, (from Oberhuber et al. 1998, also in Latif, 2001, Fig 4 therein).

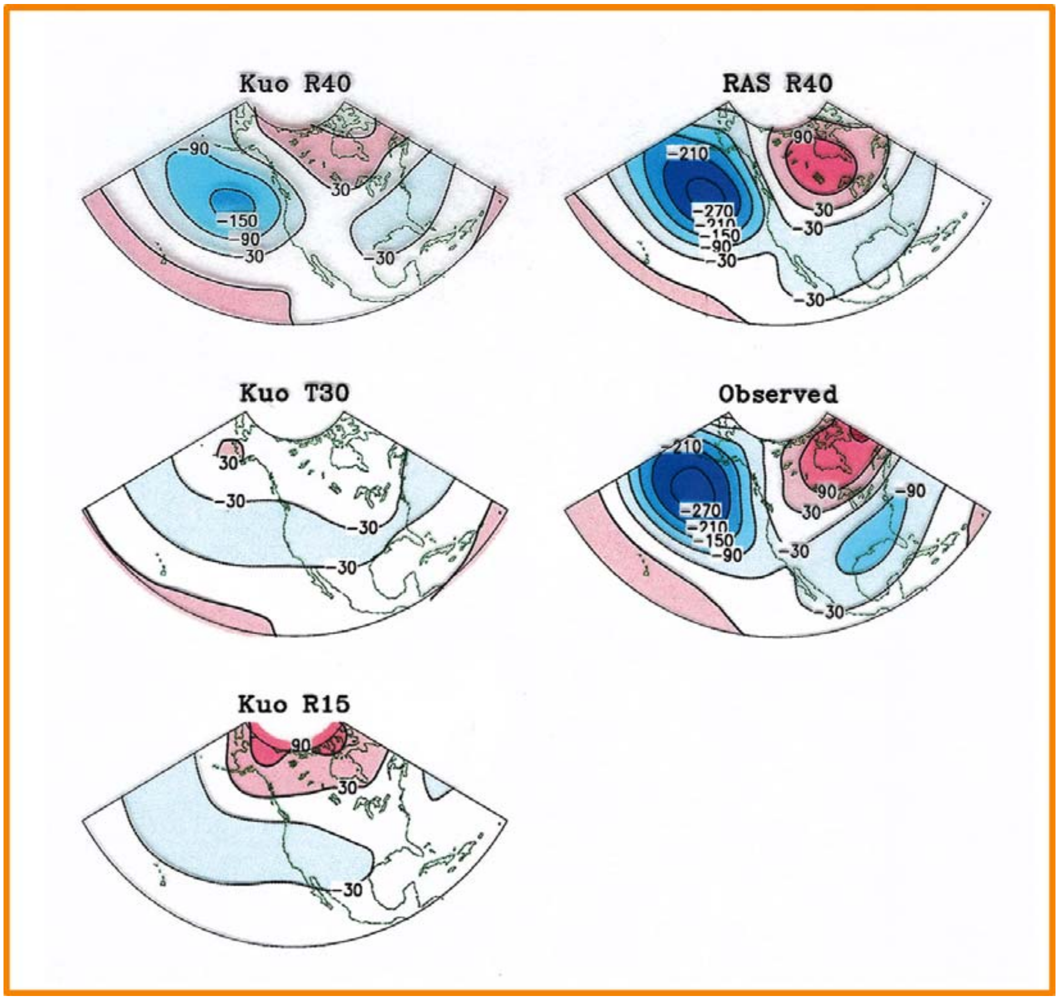

Figure 9. Development in the skill to predict the atmospheric response from tropical SST anomalies. (Courtesy J. Shukla)

Figure 10. Forecast maps from ICM,
(http://weather.icm.edu.pl/english/weathfrcst/weatherforecast.html)

Figure 11, Meteogram from ICM,
(http://weather.icm.edu.pl/index2eng.php?ver=)