Recent Developments in Predictability and Dynamical Processes (PDP)

Research: A Report by the THORPEX PDP Working Group

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Abstract

THORPEX - A World Weather Research Programme was established in May 2003 by the WMO as a ten-year international global atmospheric research and development program. THORPEX is a component of the WMO World Weather Research Programme (WWRP) and it aspires to become a successor to the fifteen-year Global Atmospheric Research Programme (GARP) that started in 1967. While GARP aimed at discovering unknown details of atmospheric dynamics and eventually led to dramatic improvements in the accuracy of weather forecasts, the stated goal of THORPEX is “Accelerating improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, the economy and the environment”. Entering its implementation phase in 2005, five working groups have been established within THORPEX, among them the Predictability and Dynamical Processes (PDP) Working Group. Discussions in this working group, including outreach activities to the international community with the aid of “interest groups” led to a summary of recent key achievements in the field of atmospheric dynamics and predictability and identified major overarching themes of THORPEX PDP research. This paper provides a summary of a selection of these themes and highlights the need for international research cooperation, including field experiments, diagnostic and theoretical studies. Research on the key THORPEX PDP research themes aims at bringing together experts from various sub-disciplines, such as short- and extended-range forecasting, predictability theory and process studies of hazardous weather, wave and vortex perspectives of atmospheric flows, and dry dynamics and complex physical processes.
Capsule

The THORPEX Predictability and Dynamical Processes Working Group gives an overview of high priority overarching research issues that THORPEX is planning to address in the upcoming years.


Introduction

The Fourteenth World Meteorological Congress (Resolution 12) in May 2003 established THORPEX: A World Weather Research Programme as a ten-year international global atmospheric research and development program. THORPEX is a component of the WMO World Weather Research Programme (WWRP) and it aspires to become a successor to the fifteen-year Global Atmospheric Research Programme (GARP) that started in 1967. While GARP aimed at discovering unknown details of atmospheric dynamics and eventually led to dramatic improvements in the accuracy of weather forecasts, the stated goal of THORPEX is “Accelerating improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, the economy and the environment”.

In February 2005, THORPEX entered its implementation phase with the approval of the THORPEX International Research Implementation Plan (TIP). The TIP called for the establishment of five working groups and charged these with the implementation of the International Science Plan. The Predictability and Dynamical Processes Working Group (PDP WG) organizes and supports international activities that involve collaboration between the research communities working on numerical weather prediction (NWP) and theoretical meteorology.

The close relationship between theoretical meteorology and the development of operational NWP models was perhaps best described by Peter Lynch (2006), one of the scientists who made notable contributions at the intersection of the two areas: “There is a strong symbiosis between numerical weather prediction and theoretical meteorology. Advances in our understanding of the physics and dynamics of the atmosphere and ocean are soon exploited in computer models, and these models themselves provide us with a powerful tool of exploring the behaviour of the real atmosphere and ocean”. Operational NWP models provide the arguably most consistently accurate solutions of the equations that govern atmospheric motions. Also, the NCEP/NCAR (Kalnay et al. 1996) and ERA40
(Uppala et al. 2005) reanalysis data sets, prepared by two of the leading operational NWP centers using their operational analysis/forecast systems, have become fertile breeding grounds for atmospheric process studies. One of the great potentials of THORPEX is that it provides an international organizational framework to organize joint activities between the academic and operational communities to strengthen the “strong symbiosis” for the benefit of society.

The members of the PDP WG are Craig Bishop, Sarah Jones, Thomas Jung, Shuhei Maeda, Istvan Szunyogh (Co-Chair), Olivier Talagrand and Heini Wernli (Co-Chair). In addition, to broaden participation, the PDP WG launched 8 Interest Groups (IGs), which are open to all members of the community and are led by the co-authors of this paper. The topics addressed by the eight IGs can be found at [http://www.ucar.edu/na-thorpeX/forum.html](http://www.ucar.edu/na-thorpeX/forum.html). The Interest Groups conduct their discussions through web-based mailing lists hosted by the National Center for Atmospheric Research (NCAR), Boulder. An archive of the messages submitted to the IGs can be reached through the links on the IG website. Those who are interested in joining one or more of the IGs should send a message to Pam Johnson at UCAR (johnsonp@ucar.edu).

The first task of the IGs was to compile a brief summary of the most important developments in their respective field in the last five years and a list of specific research issues, which the members of the given group considered to be the most important unanswered research problems in the given area. A collection of the full IG reports will be published in a WMO THORPEX publication. In this paper, we discuss those science issues from the reports that fit into one of the following five overarching themes:

- Tropical and extratropical cyclones,
- Rossby wavetrains,
- Madden-Julian Oscillation
- The relationship between dry and moist atmospheric dynamics,
- Ensemble-based prediction of forecast uncertainties.

The section “Predictability and Dynamical Processes” briefly describes, in general terms, how improved understanding of the dynamical processes can lead to better understanding of predictability. The five sections that follow, discuss the five major themes in the order they are listed above. The box “Planned Activities” gives a short overview of the relevant THORPEX research activities planned for the second half of 2008 and 2009.

**Predictability and dynamical processes**

The atmosphere is a chaotic physical system, that is, solutions of the system of equations that govern atmospheric motions are sensitive to the initial conditions. Small errors in the initial conditions lead to a complete loss of predictability after a finite time integration of the equations. An average predictability time limit can be defined, for instance, by the typical forecast time at which the root-mean-square error of the ensemble mean forecasts becomes equal to the root-mean square error of the forecast based on the climatology. While for a state-of-the-art numerical global weather prediction system the average predictability time limit is about two weeks, the evolution of the errors in the forecasts exhibits strong spatio-temporal variability.

The spatio-temporal distribution of the magnitude of the forecast errors is determined by three factors: (i) the spatiotemporal distribution of errors in the initial conditions, (ii) the spatiotemporal propagation, and amplification or decay, of the initial condition errors in the forecasts, and (iii) the
spatio-temporally varying contribution of model errors. The overall quality of a deterministic forecast can be improved by reducing the magnitude of the errors in the initial conditions and by improving the representation of the physical processes of the atmosphere in the numerical models. The overall quality of an ensemble-based probabilistic forecast can be improved by improving the representation of the uncertainties in the initial conditions and the forecast model. Since the effect of model errors can also be taken into account by statistical post-processing techniques, such as calibration of the forecast probabilities based on re-forecasts (Hamill et al. 2006), the development of improved post-processing techniques is also essential.

We note that the accuracy of initial conditions can be improved by refining the observing systems, the observing strategies and the data assimilation systems that provide the initial conditions by assimilating the observed information. In THORPEX, activities related to these three issues are planned and carried out primarily by the Data Assimilation and Observing Systems (DAOS) and Observing Strategies (OS) Working Groups. Here we only note that remarkable advances have been made in these areas in the last decade. Today forecasts for the Southern Hemisphere are of similar quality to those for the Northern Hemisphere (Simmons and Hollingsworth 2002; also see Figure 11.8 in Lynch 2006 for an update). The dramatic improvement in the quality of the Southern Hemisphere forecasts reflects the profound advances made in improving the observational coverage of the globe, developing highly accurate satellite based observing sensors, and in improving the techniques to assimilate remotely sensed observations.

Although intrinsically chaotic in nature, the atmosphere is not in a state of fully-developed turbulence: a large root-mean-square forecast error in the short- or early medium-range (about 1-7 days) over the globe, or over a limited area forecast domain, is typically the result of the erroneous forecast of a single or very few weather systems, e.g., mid-latitude cyclones. Thus, it is reasonable to expect that a better understanding of the dynamics associated with the genesis, evolution and
interaction of such weather systems would lead to a better understanding of the limits of their predictability, to their better prediction with the NWP models, and to a better representation of the uncertainties associated with their forecasts in the ensemble prediction systems.

**Tropical and extratropical cyclones**

**Tropical Cyclones.** The general physical mechanisms leading to tropical cyclone (TC) formation, or cyclogenesis, are yet to be fully elucidated, and they may differ from case to case. One may surmise that the predictability of cyclogenesis is controlled by processes on a variety of scales, from convective to synoptic scales. The nature by which these scale interactions yield a warm-core vortex with a closed surface wind circulation remains unsolved.

The most significant advances in TC forecasting to date have been on prediction of the TC location or track, using global models. Track predictions play an important role since their accuracy is the primary metric for society, tracks can be predicted with some skill by global models, and track forecasts are straightforward to verify. Over the past half-century, track forecasting has been viewed as a predominantly synoptic-scale problem in which the "steering current" can be approximated by some vertical average of the wind field. The primary synoptic features associated with the steering of the TC, such as subtropical high-pressure systems and mid-latitude and tropical upper-tropospheric troughs, are well known (Carr and Elsberry 2000a,b). However, uncertainty remains in the predictability of these synoptic systems, which can have a major effect on the translational speed and direction of the TC. Internal dynamics within the TC core are expected to provide a secondary influence on the track in most situations.

Investigations into predictability and error growth of TC track have been limited to date. A few
studies have used an entropy-based method to yield an e-folding timescale of track error growth. For example, Aberson and Sampson (2003) used this metric to suggest that 5-day forecasts may exhibit skill relative to that obtained by climatology and persistence (CLIPER). Concurrently, recent improvements to track forecasting have led some operational centers to extend the range of track forecasting from 3 days to 5 days. Recent results have also indicated that TC track forecasts based on a multi-model consensus are more accurate than those based on single models (Goerss 2006). Sophisticated multi-model ensembles have been developed to predict TC track and intensity (Weber 2005). Research into the use of ensemble prediction systems for TC forecasts must have high priority in the future.

In contrast to predictability of TC track, only limited progress has been made on predictability of TC structure, and consequently intensity, rainfall and wind distribution. A high-resolution, core-resolving model that captures dynamical and physical processes within the TC is necessary for such studies, and only one such model has been used to date for operational TC prediction (NOAA GFDL). However, several high-resolution regional research models demonstrate promise for real-time forecasting of hurricane structure (e.g., Chen et al. 2007; Davis et al. 2008), and such models will enable numerous new predictability questions to be addressed over the next decade.

Extratropical transition of tropical cyclones. A TC travelling into the midlatitudes can transform into a fast moving and intense extratropical cyclone i.e. undergo extratropical transition (ET). This process is often associated with severe weather conditions and reduced predictability at the location of the ET and further downstream at later forecast lead times (e.g. Harr et al. 2008). The changes in the structure of the cyclone during the initial phase of ET are characterized by enhanced asymmetries in the wind, cloud and precipitation fields (Kitabatake et al. 2007) so that structure
forecasts are important for countries directly affected by ET. ET events are often associated with large variability in the skill of forecasts initialized from a sequence of analyses (Jones et al. 2003). In addition, forecasts of TC structure have been found to have larger errors during ET than for a mature TC (Evans et al. 2006). Uncertainty in ET forecasts can arise due to variability in the structure and location of both the decaying TC (Klein et al. 2002) and the midlatitude trough with which it interacts (Browning et al. 2000; Ritchie and Elsberry 2007). The relative importance of processes, such as sensible and latent heat fluxes, latent heat release, frontogenesis, and baroclinic energy conversion varies between ET events. For example, enhanced upper-level ridging associated with latent heat release during ET has been shown to result in enhanced precipitation (Atallah and Bosart 2003).

**Extratropical Cyclones.** Although the first important step toward exploring the processes that lead to the formation of extratropical cyclones was taken more than a century ago by Margules, who introduced the concept of available potential energy, systematic studies of extratropical cyclogenesis in the real atmosphere, based on large statistical samples of events, could start only a few years ago when the reanalysis data sets became available.

Several recent studies, based on reanalysis data, emphasized the importance of downstream development, a process that was first described by Simmons and Hoskins (1979). In these studies, cyclogenesis is triggered by downstream propagating packets of upper-tropospheric Rossby waves although, unlike in the idealized experiments of Simmons and Hoskins (1979), the upper-tropospheric waves do not obviously originate from an upstream baroclinic development. Hakim (2003) found that surface cyclogenesis events over the western Pacific are preceded by wave packets that originate poleward of the Himalaya Plateau and develop rapidly across the North Pacific to North America. Chang (2005) examined western Pacific cyclogenesis during mid-winter (December to February) and
found that these events are strongly influenced by pre-existing upstream wave packets, which propagate along both the northern (over Siberia) and southern (the sub-tropical jet over southern Asia) waveguide. He also found that some of the cases involve interactions between pre-existing upper-level wave packets with pre-existing low-level circulation anomalies. Danielson et al. (2004) examined 41 cold-season cyclones that intensified strongly over the eastern North Pacific Ocean and found that about half of the cyclones are good examples of downstream baroclinic development.

**Rossby wavetrains**

Synoptic scale Rossby wavetrains play a central role in the downstream propagation of localized influences in the atmosphere, and they have been shown to be prevalent in the midlatitudes of both hemispheres during both warm and cool seasons (e.g., Chang and Yu 1999). Due to their dispersive nature, such wavetrains can propagate much faster than the weather systems that trigger them initially. Atmospheric wave trains can build causal relationships between weather systems that are distant in both time and space (Figure 1).

Downstream cyclogenesis, which we discussed earlier, is only one important example for the atmospheric motions Rossby waves can trigger downstream. Breaking Rossby waves (the final stage of baroclinic wave development) have been linked to episodes of heavy precipitation over the European Alps by Martius et al. (2006) and Grazzini (2007). These studies found that in some cases the precursor waves to these breaking Rossby waves can be tracked up to eight days in advance over the Asian-western Pacific region during the cool season, as well as from the US Southwest in spring. Grazzini (2007) also studied the performance of the ECMWF forecasts system for these heavy precipitation
events and found that the forecasts had higher than average skill at the synoptic scales. Wave packets can also penetrate into the (sub-) tropics, causing extreme precipitation and dust storms (e.g., Knippertz and Martin 2005). Moreover, breaking Rossby waves can influence low-frequency variability of the atmosphere (e.g., Nakamura and Fukamachi 2004; Enomoto 2004; Abatzoglou and Magnusdottir 2006).

Rossby wavetrains also play an important role in the downstream propagation of forecast errors: errors in the forecast of an upstream weather event propagate downstream with increasing forecast lead-time at the group velocity of the wavetrains. Accordingly, local improvements in the analysis, e.g., due to the assimilation of targeted weather observations, can have positive forecast effects far downstream of the location of the analysis improvement when Rossby wavetrains are present in the upper-tropospheric flow (e.g., Szunyogh et al. 2002).

In the extratropics, the triggering, propagation and breaking of Rossby wavetrains can be explained by using a single atmospheric state variable, the isentropic potential vorticity (PV). The PV distribution in the extratropical tropopause region is typically characterized by zonally oriented bands of intense PV gradients near the dynamical tropopause (the 2-pvu isoline). These bands are collocated with the upper tropospheric jet streams, and their length can reach up to several 1000 km. They can be regarded as temporally evolving “PV waveguides” for the propagation of Rossby wavetrains (e.g., Schwierz et al. 2004), constituting a key planetary-scale atmospheric flow element, both for the evolution of synoptic-scale weather systems and for the error propagation in NWP models. In the last few years, the concept of waveguides, precursor disturbances, wave propagation and amplification, and eventually downstream impacts has proven useful for several research issues on predictability and dynamical processes. It also featured prominently in the THORPEX Science Plan (Shapiro and Thorpe 2004).
Waveguides can be disturbed in many different ways (Figure 1). Common to all these wave-like disturbances is the generation of positive or negative PV anomalies along the waveguide that can induce rapid downstream dispersion of the initial wave packet. One example for such a precursor is the isentropic advection of a high-amplitude stratospheric PV vortex (i.e., a positive PV anomaly) from the polar region, whose cyclonic circulation will induce a wave-like disturbance along the mid-latitude waveguide. In many other situations, cloud condensational heating in the lower and middle troposphere produces a negative PV anomaly with associated anticyclonic circulation at the tropopause level. This heating can be associated, for instance, with ET, a warm conveyor belt ascending within an extratropical cyclone, or a mesoscale convective system. PV anomalies can be generated also when the upper-level divergent outflow from a TC or other organized convective system impinges on the sloping midlatitude tropopause. Another mechanism for inducing upper-level waveguide disturbances is related to the flow distortion by elevated large-scale topography (e.g., Greenland and the Himalaya). Chang (2005) found that existing wave packets are often enhanced by surface cyclogenesis, such increasing the potential strength of the downstream impact.

Does the existence of a precursor mechanism enhance the predictability of a severe downstream weather event? In principle, the existence of a coherent upper tropospheric trigger does not guarantee better predictability, since uncertainties in the prediction of the physical processes that affect the initiation and propagation of the Rossby wave packet and in the prediction of the processes that determine the lower-tropospheric conditions at the location of the downstream event can limit predictability. However, the empirical evidence shown by Grazzini (2007) suggests that in a state-of-the-art NWP model the representation of the dynamical processes along the waveguides is sufficiently accurate to ensure higher than average predictability of some of the downstream events.
Madden-Julian Oscillation (MJO)

The stated goal of THORPEX is to improve forecasts up to two weeks lead-time, which is the typical predictability time limit using a state-of-the-art NWP model. THORPEX recognizes, however, that for certain atmospheric flow configurations the predictability time limit can be longer than that. An atmospheric dynamical process that has the potential to lead to extended predictability in the extratropics is MJO, which is the dominant mode of variability in the Tropics on time scales exceeding one week and less than a season (e.g., Lau and Waliser 2005). The phrase “potential” is used here, because global models have major difficulties with simulating and predicting the MJO, and it is not possible to foresee all consequences of a better representation and prediction of the MJO in the models.

What we know with certainty are that (i) MJO has a significant impact on cyclogenesis in the eastern North Pacific (Maloney and Hartmann 2000), the Atlantic (e.g., Mo 2000), the western North Pacific (Sobel and Maloney 2000), the Australian basin (Hall et al. 2001) and the South Indian Ocean (Bessafi and Wheeler 2006) and that (ii) while statistical predictive models of the MJO display useful predictive skill out to at least 15-20 days lead time (Waliser et al. 1999; Lo and Hendon 2000; Wheeler and Weickmann 2001), the predictability time limit of the MJO in NWP models is much shorter than that (e.g., Vitart 2003). Global circulation models (GCMs) not only have difficulties with predicting the MJO, but they also struggle to maintain a realistic MJO. Slingo et al. (1996) found that none of the atmospheric GCMs that took part in the Atmospheric Intercomparison Project were able to capture the spectral peak associated with the MJO. A recent evaluation of the coupled atmosphere-ocean models that provided simulation results for the Intergovernmental Panel on Climate Change (IPCC) fourth Assessment Report showed only slight improvement in the maintenance of the MJO (Lin et al. 2006).
The aforementioned results suggest that model errors are likely to be the main obstacle to predicting MJO events. In fact, Vitart et al. (2008) found that using an improved representation of the mixing in the upper ocean and a different cloud parameterization helped maintaining the MJO for 8 more days. More recently, Miura et al. (2007) found that a 7-km resolution atmospheric model running on the Earth Simulator, a Japanese supercomputer developed for running more realistic global simulations, was able to maintain an MJO with realistic structure over a period of 1 month. This result suggests that significantly increasing the resolution of operational weather forecasting systems may help to reduce model errors that currently hamper more realistic model forecasts of the MJO.

The only study, up to this day, that made an attempt to quantify the potential improvement of the forecast skill in the extratropics due improved representation of the MJO is Ferranti et al. (1990). This study found that an improved representation of the MJO in the ECMWF forecast model, achieved in that case by relaxing the tropical circulation towards the analyses, could lead to a significant increase of skill in the extratropics for more than 10 days. While this experimental design has the potential to lead to an overestimation of the potential forecast improvement in the extratropics, as it assumes perfect predictability in the Tropics, it would be desirable to carry out similar experiments with current state-of-the-art models.

**The role of diabatic processes**

Diabatic processes, in particular the release of latent heat due to cloud condensation, but also surface fluxes of sensible and latent heat, can have a significant impact on the structure, evolution and predictability of weather systems. In terms of PV, latent heat release is primarily associated with
production of PV in the lower troposphere and destruction of PV above the level of maximum diabatic heating. This indicates that the primary effect of moist processes is the generation or enhancement of cyclonic circulations in the lower troposphere and anticyclonic circulations in the upper troposphere.

Diabatic processes have been known for a long time to play a primary role in the development of such tropical weather systems as organized convection and TCs. In contrast, in the extratropics, baroclinic instability has been traditionally regarded as the key mechanism for the development of cyclones and their accompanying frontal structures, with diabatic processes playing a secondary, typically intensifying, role. A more complex picture started to emerge, however, from a series of recent studies that provide evidence that in a substantial number of cases diabatic processes (i) have crucial impact on the formation of intense extratropical weather systems, (ii) have a major influence on the downstream effects of these weather systems, and (iii) have a major influence on predictability in the midlatitudes. In what follows, we review some of the most important results of these studies.

The idealized study of Lapeyre and Held (2004) found that while dry and not very moist atmospheres are primarily dominated by the formation of baroclinic waves, very moist atmospheres are dominated by finite amplitude vortices. These vortices are reminiscent of diabatic Rossby waves (DRWs), which are diabatically regenerated, positive, low-level PV anomalies that propagate rapidly along intense baroclinic zones. (See Moore and Montgomery (2004) for an overview and discussion of the wave/vortex aspects of the phenomenon.) The significance of these vortices is that they can exist and propagate without forcing from an upper-level anomaly and may act as precursors for “bottom-up” cyclone intensification when they interact with an intense upper-level jet (Wernli et al. 2002). Despite the coherent nature of the phenomenon, current NWP models have serious difficulties with predicting DRWs. Diabatic processes are also thought to play a potentially important role in creating the initial perturbations that can lead to rapidly growing “bottom-up” instabilities in regions of enhanced baroclinicity (Hoskins et al. 2000). These structures can be captured by singular vector calculations and
are often used to identify the optimal locations for the deployment of targeted observations (e.g., Langland 2005) and to generate initial ensemble perturbations (e.g., Buizza 2006). The rapid growth of these perturbations can be explained by *PV unshielding*, a process in which a positive PV anomaly becomes unshielded by the eastward and westward displacement of an upper and lower negative PV anomaly due to the advection by the zonal shear flow (Badger and Hoskins 2001).

Massacand et al. (2001) found the first example for the potentially important downstream impact of diabatic processes in the extratropics. They showed that the transport of low-PV air into the upper troposphere by a warm conveyor belt was crucial for downstream Rossby wave breaking, which in turn led to an event of Alpine heavy precipitation. Knippertz and Martin (2005) observed a similar link between an upstream conveyor belt and a heavy precipitation event over northern Africa. These results indicate that diabatic processes can strongly alter the effects of an upstream extratropical cyclone on the downstream large-scale flow. In such situations, an accurate simulation of the warm conveyor belt, for instance in the western ocean basins, might be essential for a high-quality medium-range forecast over the downstream continents. This hypothesis is supported by the study of Danielson et al. (2004), who found that for those eastern North Pacific cyclones that were influenced by downstream propagation of eddy energy from cyclones over the western North Pacific, the primary energy source was a warm conveyor belt type ascent in the warm sector of the upstream cyclones.

Investigating the relationship between predictability and dynamical processes for the “no-surprise” east-coast snowstorm of January 2000, Zhang et al. (2002) found that forecast errors at the synoptic scales were preceded by errors associated with moist convection on scales smaller than 100 km. This process of upscale error propagation can be observed in both the models that use parameterized convection and the models that explicitly resolve convection. Walser et al. (2004),
however, analyzing results from convection-resolving simulations of Alpine heavy precipitation events, found that topographic triggering of the convection enhanced the predictability.

**Ensemble-based prediction of forecast uncertainties**

One of the most important post-GARP developments in NWP has been the implementation of operational ensemble prediction systems, which started in the early 1990s at ECWMF and NCEP (e.g., Kalnay 2002; Palmer and Hagedorn 2006). A close collaboration between the operational and the research centres in the area of ensemble prediction will be facilitated by the creation of the TIGGE database. TIGGE has been a major investment of the operational centres to support the researchers community, as it provides scientists unprecedented, nearly real-time, access to ensemble forecast products of several operational weather prediction centres. (For more information on TIGGE visit [http://tigge.ecmwf.int](http://tigge.ecmwf.int).)

Despite the more than fifteen years of operational experience and the hundreds of research papers written on the subject, questions on how ensemble forecasts should be created and used remain open. A prominent difficulty is that the object of an ensemble-based prediction, basically a probability or a probability distribution, is not better known a posteriori than it was a priori. In fact, the predicted object has no objective existence and cannot be possibly observed at all (e.g., Toth et al. 2006). As a consequence, validation of an ensemble prediction system requires careful statistical analysis of a large number of events. It is of little use to speak of the quality of ensemble-based predictions of the probability distribution on a case-to-case basis (e.g., Talagrand et al. 1997).
One potential approach to evaluate the performance of an ensemble is to evaluate the extent to which the vector sub-space of ensemble perturbations spans the space of forecast error. For instance, this approach was used to compare the performance of the ensemble prediction systems of NCEP and ECMWF (Wei and Toth 2003). Kuhl et al. (2007) applied a similar approach in localized regions of the atmosphere and found that the ensemble captured the space of forecast errors most efficiently in cases of rapid error growth. We note, however, that this concept leads to a practical measure only if we assume that the space of uncertainties is linear.

Experience accumulated with the operational ensemble forecasting systems suggest that present scores saturate for a value of ensemble size N in the range 30-50, independently of the quality of the score (e.g., Richardson 2001). On the other hand, theory tells us that according to chi-square statistics, with N=30 and a true variance of 1, the sample variance has a 95% chance of lying between 0.56 and 1.57; i.e. variance estimates are very inaccurate. With N=100, the corresponding 95% confidence interval (0.74,1.29) is significantly smaller. In the face of this theoretical fact, how can we explain our aforementioned experience that the forecast scores saturate at N=30-50? There are at least four possible explanations: (i) Scores have been implemented so far on probabilistic predictions of events or one-dimensional variables (e.g., temperature at a given point). The situation might be different for multivariate probability distributions, but for those the large verification sample needed to obtain stable verification statistics may not be attainable. (ii) Probability distributions in the case of one-dimensional variables are most often unimodal. The situation might be different for multi-modal probability distributions, as produced for instance by multi-model ensembles. (iii) Saturation is due to the characteristics of synoptic-scale atmospheric dynamics. The situation might be different for mesoscale ensemble prediction. (iv) Lack of direct measure of accuracy of the predicted error variance.
One may also want to have a larger ensemble to better resolve the probability distribution or to better predict rare events. However, these goals may be elusive: (i) Are there any users who will ever care whether the probability for rain tomorrow is 123/200 rather than 124/200? (ii) The verifying sample needed to check the reliability of a large ensemble may be prohibitively large. Assume that the predicted probability is $1/N$ for a given event $E$ and that we have one 10-day forecast every day. $E$ has to occur roughly $cN/10$ times, where $c$ is of the order of a few units, before reliability can be assessed. If the event occurs about four times a year, we must wait 10 years for $N = 100$, and 50 years for $N = 500$ ($c = 4$). We can conclude that the reliable probabilistic prediction of an even moderately rare event is simply impossible. The problem of size of verifying sample will remain, even if it can be mitigated to some extent by using reanalyses or re-forecasts for validation. More work is clearly needed to identify the useful size of an ensemble and the practically attainable size of a verification sample.

There is a strong consensus between members the operational and research communities that the ensemble approach is the way of the future, for both data assimilation and weather prediction. But no strong views have emerged, yet, on the format of the future ensembles. Must they consist of mutually equal elements (or of subsets of mutually equal elements, produced for instance by different models), or must they contain, as is the case now, individual elements of higher statistical quality (higher resolution, or control forecasts)? The present situation is somewhat hybrid, the predicted ensemble being a kind of auxiliary to a statistically more accurate higher resolution forecast. Must we aim at a situation where the predicted object will be a probability distribution?
Activities Planned for 2008 and 2009

THORPEX Pacific Asian Regional Campaign (T-PARC). T-PARC will be the second major, and so far the largest, field campaign of THORPEX, which follows the Atlantic-THORPEX Regional Campaign (A-TReC) in 2004. T-PARC will have two major phases: a summer-autumn phase that will overlap with the 2008 typhoon season and a winter phase that will take place in January and February of 2009. The first phase will take part in conjunction with the Tropical Cyclone Structure 08 (TCS08) experiment and will focus on the life cycles of typhoons in the Northwest Pacific. It will include both basic research components, mainly focusing on dynamical processes associated with tropical cyclogenesis, ET, and the downstream effects of ET. Analysis/forecast experiments will be carried out to study the predictability of the track, intensity, and re-curvature of TCs, and to investigate changes in extratropical predictability due to ET. The winter phase will focus on the genesis and downstream effects of extratropical cyclones. The detailed science plan, experimental design overview, and the latest information on T-PARC can be found at http://www.ucar.edu/na-thorpex/PARC.html.

Year of Tropical Convection (YOTC). YOTC is the first planned collaborative activity between THORPEX and the World Climate Research Program (WCRP). The recognition that poor representation of tropical convection in the global circulation models is one of the major road blocks to further improve the quality of both numerical weather predictions and climate simulations motivated THORPEX and WCRP to organize the Workshop on the Organization and Maintenance of Tropical Convection and the Madden Julian Oscillation in Trieste, Italy, in March 2006 (Moncrieff et al. 2007). One of the recommendations made by the workshop was the organization of YOTC, which will bring
together observational information from already existing platforms and analysis and forecast information from operational centers for a one-year period. YOTC will also take advantage of the newly available research and modeling framework of explicitly \textit{cloud-system resolving models} (CSRMs). CSRMs are expected to lead to improved parameterization for convective organization and the better representation of upscale effects of organized precipitating tropical convection (Moncrieff and Liu 2006). A detailed science and implementation plan of YOTC is currently under development by a science planning group led by Mitch Moncrieff of NCAR and Duane Waliser of JPL/CALTECH. The latest version of this document is available at

\url{http://hydro.jpl.nasa.gov/tmp/WCRP.WWRP.YOTC.scienceplan.pdf}.
References


Knippertz, P. and J. E. Martin, 2005: Tropical plumes and extreme precipitation in subtropical and


Moncrieff, M.W., M.A. Shapiro, J. M. Slingo and F. Molteni, 2007: Collaborative research at the intersection of weather and climate, WMO Bulletin, 56, 204-211.


Figure captions

Fig. 1. Schematic illustration of the propagation of hydro-dynamical influences along a PV waveguide. Also shown are the atmospheric processes that can cause the initial upstream disturbances and the weather events these disturbances can trigger downstream.