WORLD METEOROLOGICAL ORGANIZATION

Weather Research in Europe

A THORPEX European Plan

Version 3.1

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1. THE THORPEX EUROPEAN PLAN

1.1 International background

THORPEX, an element of the World Weather Research Programme (WWRP is an international research and development programme responding to the weather related challenges of the 21st century to accelerate improvements in the accuracy of 1-day to 2- week high impact weather forecasts for the benefit of society, the economy and the environment.

This requires research into:

- Global-to-regional influences on the evolution and predictability of weather systems;
- Global observing system design and demonstration;
- Targeting and assimilation of observations;
- Societal, economic, and environmental benefits of improved forecasts.

The THORPEX International Science Plan (WMO/TD-No. 1246; WWRP/THORPEX No. 2) was published in November 2003 and this was followed by a THORPEX International Research Implementation Plan (WMO/TD-No. 1258); WWRP/THORPEX No. 4) in December 2004 (both plans are available on www.wmo.int/thorpex/plans.html).

1.2 Working Groups

Two THORPEX Working Groups have been charged by the International Core Steering Committee (ICSC) for THORPEX to develop and coordinate specific activities for three of the four THORPEX sub-programmes:

- Predictability and Dynamical Processes Working Group (PDP WG) – global-to-regional influences on the evolution and predictability of weather systems; and
- Data Assimilation and Observing Systems Working Group (DAOS WG) – global observing system design; targeting and assimilation of observations.

The World Weather Research Programme (WWRP) Societal and Economic Research and Applications Working Group has, as one its tasks, the responsibility for the co-ordination of the assessment of the societal, economic and environmental benefits of improved forecasts for the THORPEX Programme.

To complement and support the work of these Working Groups, the ICSC established the Global Interactive Forecasting System (GIFS) – THORPEX Interactive Grand Global Ensemble Working Group (GIFS-TIGGE WG). The initial task given to the GIFS-TIGGE WG was to develop and test a global multi-model ensemble prediction system and this is a continuing task.

The THORPEX sub-programmes have been designed to:

- Increase knowledge of global-to-regional influences on the initiation, evolution and predictability of high-impact weather;
- Contribute to the development of advanced data assimilation and ensemble prediction systems;
- Contribute to the design and demonstration of global *interactive forecast systems (GIFS)* that allow information to flow interactively among forecast users, numerical forecast models, adaptive data-assimilation systems and observations to maximise forecast skill (this includes the *THORPEX Interactive Grand Global Ensemble* (TIGGE) that develops and evaluates multi-model/multi-analysis ensemble prediction systems);
- Contribute to the development and application of advanced methods that enhance the utility and value of weather forecasts to society, economies and environmental stewardship;
- Carry out THORPEX Observing System Tests (TOSTs) and THORPEX Regional field Campaigns (TReCs). TOSTs: i) test and evaluate experimental remote sensing and *in-*

situ observing systems, and when feasible, demonstrate their impact on weather forecasts; ii) explore innovative uses (e.g., targeting) of operational observing systems. TReCs are operational forecast demonstrations contributing to the design, testing and evaluation of all components of interactive forecast systems;

- Conduct regional and global campaigns as demonstrations and assessments of new observing technologies and interactive forecast systems. Thereby, THORPEX will provide guidance to the World Weather Watch (WWW) and forecast centres on improvements to forecast systems, and to relevant bodies, such as the WMO Commission for Basic Systems (CBS), concerning optimisation of global and regional observing systems;
- Address the influence of inter-annual and sub-seasonal atmospheric and oceanic variability on high-impact forecasts out to two weeks, and therefore aspire to bridge the "middle ground" between medium-range weather forecasting and climate prediction. This provides a link with programmes addressing the improvement of sub-seasonal, seasonal, and global climate change prediction systems;
- Demonstrate all aspects of THORPEX interactive forecast systems, over the globe for a season to one year to assess the utility of improved weather forecasts and user products;
- Coordinate THORPEX research with the World Climate Research Programme (WCRP) and the relevant components of WWRP to address the observational and modelling requirements for the prediction of weather and climate for two weeks and beyond; and
- Facilitate the transfer of the results of THORPEX weather prediction research and its operational applications to developing countries through the WMO by means of appropriate training programmes.

1.3 Regional Committees

Nations and consortia of nations have established THORPEX Regional Committees (RCs) that define regional priorities for participation in THORPEX within the framework of the THORPEX International Science and Implementation Plans. These THORPEX Regional Committees develop regional activities within the framework of the international plans. They facilitate provision of funding, logistical and other support, planning, coordination and implementation of THORPEX activities conducted by the region with respect to the THORPEX International Research Implementation Plan. To date Regional Committees have been established for Asia (ARC), Africa (AfRC), Europe (ERC), North America (NARC) and the Southern Hemisphere (SHRC).

In addition to the THORPEX Science and Implementation Plans, the Regional Committees have developed a series of regional plans that reflect key issues in their areas of interest and the remainder of this document sets out European Plans for THORPEX.

1.4 Structure of the European plan

The European plan builds upon the THORPEX Science Plan and focuses on the implementation of the scientific elements which broadly fit with European requirements. The details of the plan reflect the special circumstances of meteorological research in Europe. There are a large number of nations, each with its own research funding structure and its own national meteorological service. These are complemented by international organisations, including EUMETNET, EUMETSAT and ECMWF, as well as trans-national research and coordination agencies, such as the Framework Programmes, and the COST. Three of the national meteorological services and ECMWF run global numerical weather prediction (NWP) systems, two of which produce deterministic and ensemble forecasts out to 15 days. Many of the national meteorological services run regional NWP systems. These regional systems are organised in a number of consortia and are used also by the research community. In general, there is a strong history of the European research community working with both global and regional operational forecast models in collaboration with the operational meteorological services / consortia.

The diversity of meteorological research in Europe influences the priorities that have been adopted in the plan, notably a significant emphasis on model development, data assimilation, ensemble prediction and limited area modelling.

The plan begins with a description of the main weather-related societal and economic impacts resulting from the weather phenomena that affect Europe. The next section identifies the scientific challenges that have to be met in order to improve the prediction of these meteorological phenomena and to realise the potential societal and economic benefits of improved predictions. Action plans are then presented for the THORPEX research areas: Predictability and Dynamical Processes (PDP), Data Assimilation and Observing Systems (DAOS), ensemble prediction and the use of the THORPEX Interactive Grand Global Ensemble (TIGGE) and Societal and Economic Research and Applications (SERA).

2. WEATHER PHENOMENA AND THEIR IMPACTS

The impact of weather on Europe arises through a widely varied list of “challenging” weather phenomena. The predominant weather-related impacts are strong mean winds and severe gusts, heavy precipitation / rapid snow melt leading to flooding and landslides, heavy snowfall, freezing rain, hail, lightning, heat waves or periods of extreme cold, drought, fog/poor visibility, strong vertical wind shear, prolonged periods of strong temperature inversions leading to poor air quality with associated impacts such as health risks and damage to crops; severe coastal tides, forest fires, avalanches These impacts arise due to specific meteorological phenomena many of which differ from region to region. The table below lists the most important such phenomena, their frequency and the parameters potentially associated with societal and economic impacts. Further details of the individual phenomena are given in the Annex. Research in European THORPEX aims to investigate the evolution of these weather phenomena, to quantify the factors that limit their predictability and to contribute to the development of NWP systems leading to improved forecasts of their impacts.

High-Impact Weather Phenomena	Specific scientific challenges	Frequency Time scales	Potential Societal and Economic Impacts
Blocking	• Quantify predictability of and understand processes responsible for onset, maintenance and breakdown. Identify precursors to blocking • Relate blocking to low-frequency (sub-seasonal to interannual) variability	Freq: av. <10% 5-14 days or longer	Heat waves, cold spells, droughts, air quality, forest fires, crop losses, water resources, power supply
Extratropical cyclones	• Assess role of upper-level anomalies • Investigate sensitivity in low and mid-troposphere.. • Quantify role of moisture and surface fluxes • Reduce errors in initial conditions	1/week 2-4 days	Wind, precipitation / floods, snow and ice, disruption to ground and air traffic
Polar weather (polar lows, arctic fronts)	• Enhance understanding of processes/ predictability • Improve representation of convection/snow fall, surface fluxes, clouds, PBL • Identify role of interaction with upper-level features	1-3 days	Snow, ice, strong winds
Mediterranean cyclones	• Quantify contributions to cyclogenesis from orography, strong surface fluxes, mesoscale upper-level structures • Identify which factors determine their (small) size and their track • Investigate development of tropical-cyclone-like systems and relate to polar lows	1/week (winter) 1/month (summer) 1-3 days	Precipitation, wind
Deep mid-latitude convection	• Quantify factors that determine timing and organization: relative influence of forcing factors, relative influence of synoptic-scale and local factors • Assess realism of mesoscale / high-resolution forecasts	Time scales >=1day	Lightning, hail, heavy precipitation, wind

High-Impact Weather Phenomena	Specific scientific challenges	Frequency Time scales	Potential Societal and Economic Impacts
	• Identify role in predictability of parametrizations vs. explicit convection • Utilise results of COPS, D-PHASE, E-TReC		
Orographic flow systems (tip jets, föhn, bora, mistral, mountain waves)	• Quantify predictability related to upper-level features, air-sea / air-surface interaction, upscale effects, mountain waves, small-scale structures, interaction with cold-air pools and valley flows • Inclusion of sub-grid scale orographic information in models • Data assimilation in mountainous regions	1-3 days	Wind, (forest) fires, air safety, air quality (in the presence of local cold-air pools)
Upper-level forcing: PV Streamers and Rossby-wave breaking	• Accurate representation of wave-mean flow interaction • Quantify relative importance of different conditions (ambient, local transient, orography) • Prediction of evolution of PV streamer (mesoscale, interactions with surface, structure)	1/week 2-4 days	(heavy) precipitation, Foehn, dust/air quality, convection, floods
Upper-level forcing: cut off low systems	• Represent evolution and structure in NWP systems • Predict interaction between cut-off low / convection and resulting precipitation distribution • Quantify troposphere - stratosphere exchange • Assess mechanisms responsible for low predictability	1 / two weeks (summer) 1 / month (winter)	Severe convection, floods, extreme precipitation in centre when over warm sea
Structure and dynamics of boundary layer	• Improve modelling and utilise observations of boundary layer processes • Enhance understanding of these processes • Investigate representation and role of BL moisture	1-3 days	Rotors over airports, pollution levels in cities, initiation of severe convection, heavy precipitation along the Alps
Tropical influences: downstream impact of ET	• Quantify relative roles of tropical and extratropical perturbations as sources of uncertainty • Assess factors that control Rossby wave triggering: importance of TC structure, interaction with jet • Determine importance of physical parameterizations	Average 5ET /yr in Atlantic 3 days to 2 weeks	Increased uncertainties in forecasts (wind, precipitation), floods
Tropical influences: organized tropical convection & MJO	• Quantify impact on midlatitude predictability over Europe, upscale effects	14 days 6h – 2 days (tropical prediction)	Potential increase in predictability
Tropical influences: West African Monsoon	• Quantify importance of West African Monsoon as source of moist tropical air • Determine influence of modulation of subtropical jet	3-14 days	Predictability of midlatitude cyclones, tropical cyclogenesis, dust events
Polar influences	• Sparse data, strong orographic and surface forcings	3-14 days or longer	Influence on predictability
Heat Lows	• Quantify interaction of surface forcing and synoptic environment • Assess importance of West African heat low for European predictability	3-7 days	Heat waves, wind, midlevel intrusions such as the 'Spanish plume'.

3. SCIENTIFIC CHALLENGES

3.1 Predictability and Dynamical Processes

Scientific challenges that need to be addressed in European PDP research are related to diagnosing the dynamical processes that are responsible for reduced predictability in NWP systems, identifying the areas in which theoretical advances are necessary, and working to bridge the gap between theory and operational NWP systems. The techniques used include diagnosis of real cases using operational NWP systems including their data assimilation and ensemble prediction capabilities, developing climatologies of forecast error, and applying numerical experiments with idealised and low dimensional models or with complex models in simplified situations. In the following, the scientific challenges are related to the themes considered by the PDP interest groups.

Role of Rossby wave dynamics in predictability

Synoptic scale Rossby wavetrains play a central role in the downstream propagation of localized influences in the midlatitudes of both hemispheres during both warm and cool seasons. Due to their dispersive nature, such wavetrains can propagate much faster than the weather systems that trigger them initially. Thus, atmospheric wave trains can build causal relationships between weather systems that are distant in both time and space. The propagation of Rossby wave trains is linked intrinsically with baroclinic development. The focus of the theory of baroclinic growth is the mutual interaction of counter-propagating Rossby waves, propagating on opposing meridional PV gradients. In the atmosphere, these opposing PV gradients are typically concentrated near the surface and at the tropopause. Sustained growth is possible because the two counter propagating Rossby waves can phase-lock in a mutually amplifying configuration. In the final stages of baroclinic wave development, breaking Rossby waves lead to the formation of potential vorticity (PV)-streamers and cut-off lows. Rossby wavetrains and the associated PV streamers can trigger midlatitude and (sub-)tropical cyclogenesis downstream, contribute to episodes of heavy precipitation over the European Alps, and penetrate into the (sub-) tropics, causing extreme precipitation and dust storms. Breaking Rossby waves can influence low-frequency variability of the atmosphere. 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.

Scientific challenges are associated with identifying the processes responsible for Rossby wavetrain triggering, propagation and breaking, assessing their role in predictability on a variety of temporal and spatial scales, and quantifying their representation in numerical weather prediction models. In order to make progress, the mismatch between the capabilities of theory and the description of the atmosphere in forecast models must be addressed, so that theoretical results can be applied to identify forecast error and propose solutions. This will require both advancing theoretical concepts to higher levels of complexity as well as comparing theoretical results with real atmospheric cases in an NWP framework.

Weather prediction on sub-seasonal time scales

Operational centres are moving towards predictions on the sub-seasonal time scales. There are a number of dynamical systems and processes that potentially influence the extratropical predictability at these extended ranges. Of particular interest for Europe are organised tropical convection, especially the Madden Julian Oscillation (MJO), the monsoon regimes, the interaction between the land or ocean surface and the atmosphere, and stratospheric – tropospheric interactions (see discussion of blocking below).

The MJO is the dominant mode of variability in the Tropics on time scales exceeding one week and less than a season. However, although statistical predictive models of the MJO display useful predictive skill out to at least 15-20 days lead time, the predictability time limit of the MJO in NWP models is much shorter. Typically, the waves propagate at the wrong phase speed and decay prematurely. Recent studies suggest that model error is likely to be the main limitation in predicting an MJO event, and that increasing the resolution of operational weather forecasting systems significantly may help to reduce model errors and lead to more realistic MJO forecasts. Scientific challenges are associated with improving our knowledge of the interaction between convection and the large-scale wave, quantifying the factors responsible for the MJO development and propagation, and identifying the sources of errors in NWP models. Furthermore, the consequences for extratropical predictability of a better representation and prediction of the MJO must be assessed.

In view of its importance for Europe, the West African Monsoon is discussed in a separate section below. For the South Asian summer monsoon, its onset and the start and end of active and break phases are very important weather forecast problems. For the East Asian Summer Monsoon, there is similar interest in the prediction of the onset, movement and end of the Baiu-Meyu front that brings important rain to much of this region outside the tropics. The processes that control these features and their impact on extratropical predictability need to be determined.

In recognition of the importance of improving the representation of tropical convection in global atmospheric models, WCRP and WWRP-THORPEX have implemented a programme (the Year Of Tropical Convection (YOTC)[1]) of coordinated observing, modelling and forecasting of organized tropical convection and its influences on predictability. The scientific focus is on precipitation systems organized on meso-to-large scales. The emphasis on time scales up to seasonal enables critical issues at the intersection of weather and climate (seamless prediction) to be addressed at the process level. Key uncertainties in the prediction of global weather and climate are the main targets – the MJO and convectively coupled waves, intra-seasonal variability of monsoons, easterly waves and tropical cyclones, tropical-extra-tropical interaction, and the diurnal cycle. The original "Year" has been extended to cover a two year period, 1 May 2008 to 30 April 2010, to include the T-PARC and TCS08 field experiments and both La Niña and El Niño conditions. An important challenge for European THORPEX will be to utilise the YOTC dataset to quantify the impact of tropical convection on extratropical predictability.

Predictability of tropical cyclones and of their extratropical transition

The most significant advances in tropical cyclone forecasting to date have been in the prediction of the tropical cyclone location or track, using global models. In contrast, only limited progress has been made on predictability of tropical cyclone structure, and consequently intensity, rainfall and wind distribution. A tropical cyclone 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. The impacts during the initial phase of ET are characterized by enhanced asymmetries in the wind, cloud and precipitation fields so that both track and structure forecasts are important for countries directly affected by ET. Although European countries are not influenced directly by tropical cyclone landfall or the early stages of extratropical transition, a number of European weather services do provide operational tropical cyclone forecasts from their global models. In addition, several subtropical cyclones have recently affected Europe.

Scientific challenges are associated with assessing the relative importance for tropical cyclone forecasts of the following factors: model resolution, model physics, surface fluxes, and coupling atmospheric and ocean models. For ET, the representation in NWP models of structure and intensity changes during tropical cyclone decay are not well known.

The impact of extratropical transition on downstream midlatitude predictability

The ET of a tropical cyclone can influence the midlatitude circulation far downstream of the ET event itself. Often, the downstream perturbations from the extratropical transition are related to reduced predictability that spreads to near-hemispheric scales over periods of days.

[1] *www.ucar.edu/yotc*

Impacts on predictability arise due to errors associated with the representation of the tropical cyclone, of the midlatitude flow, and of their interaction.

Scientific challenges are associated with obtaining and assimilating crucial observations, quantifying the relative importance of the specification of initial conditions and the representation of physical processes, and assessing whether representing the tropical cyclone structure (requiring high resolution) or capturing the synoptic-to planetary scale flow (requiring global models) results in improved forecasts. Furthermore, research is needed on designing initial perturbations and stochastic physics for improved ensemble forecasts of tropical cyclones, ET, and its downstream impact

Theoretical aspects of ensemble prediction

The main scientific challenges related to ensemble prediction systems (EPS) are discussed in the TIGGE section. Here we consider the theoretical aspects that contribute to the PDP working group. The rationale behind an EPS is to use an ensemble to span the number of probable evolutions of the atmosphere, given uncertainty in the initial conditions for the forecast and model error. There are many ways to represent these sources of uncertainty, but their definition will have a major influence on the range of evolutions that is spanned. Thus a scientific challenge is associated with the understanding both the dynamical background and the impact on an EPS of the methods used as well as developing new techniques. One approach is to describe the evolution of initial PV structures using Rossby wave components, as used to describe baroclinic wave development. The initial perturbations must somehow represent errors in the analysis that could grow rapidly - these need not be the fastest growing precursors since errors are dependent upon the observing network and data assimilation system.

It is still an open question as to how information from an ensemble based prediction system should be used. The main difficulty is that the object of an ensemble-based prediction, basically a probability or a probability distribution, has no objective existence and cannot be observed. 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. Thus a major theoretical challenge is associated with defining methods to evaluate ensemble forecasts. Further challenges are related to assessing the benefits or lack thereof of increasing ensemble size as well as determining the format of future ensembles

Atmospheric blocking, low-frequency variability and their role in predictability

Blocking and its predictability are of great importance to Europe on all time-scales. One perspective on blocking is that it is associated with the reversal of the usual meridional contrast in potential temperature on the dynamical tropopause (the 2PVU potential vorticity surface). This occurs through a Rossby wave breaking process that is predominantly cyclonic or anticyclonic depending on the location and time of year. It is thought that the existence and nature of individual wave-breaking events depends on an interaction between a synoptic system and the ambient planetary scale flow. One hypothesis for the nature of the North Atlantic Oscillation (NAO) is that NAO- is a description of a situation with frequent cyclonic wave-breaking in the NW Atlantic and NAO+ is the situation in which it is infrequent. However, the link is not obvious because other research has shown that the NAO pattern is associated with low frequency variability (timescales > 20 days), rather than the faster timescales associated with wave breaking in individual systems. Challenges are associated with the developing these ideas further, and investigating the ability of prediction models to simulate the occurrence and nature of Rossby wave breaking.

The influence of stratospheric variability on the troposphere on timescales beyond 10 days has been demonstrated as important in numerous recent studies. Although the mechanism for this coupling remains unclear, there are some suggestions that a link between stratospheric variability and the properties of tropospheric Rossby waves, such as their direction of breaking, is implicated. Examining regions of the atmosphere, such as the stratosphere, with long dynamical memory is vital as operational centres attempt to push the boundaries of their prediction capability beyond the traditional 7-10 day limit.

The impact of moist processes on dynamical processes and predictability in the extratropics

Moist 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. The primary effect of latent heat release within so-called warm conveyor belts associated with extratropical cyclones is to generate/enhance cyclonic circulation systems in the lower and anticyclonic circulations in the upper troposphere, which in turn can strongly influence the downstream flow evolution. Concerning the effects of surface fluxes on the synoptic-scale flow, a more general theoretical framework is sorely needed. In contrast to dry and weakly moist atmospheres that are primarily associated with the formation of baroclinic waves, finite amplitude vortices dominate in a very moist regime. These vortices are reminiscent of the concept of diabatic Rossby waves and can act as precursors for explosive cyclone intensification when interacting with an intense upper-level jet. Continental warm-season heavy precipitation clusters constitute a different type of coherently propagating and diabatically driven weather systems. Severe predictability limits exist due to upscale error growth imposed by small-scale convection; however, this influence on predictability might vary strongly for differing synoptic situations and topographic control.

Scientific challenges are associated with quantifying the impact of diabatic processes on the evolution of different types of extratropical cyclones, Rossby waves and the downstream flow development; improving the basic understanding of the role of surface fluxes for synoptic and mesoscale weather systems in the extratropics; identifying systematic model deficiencies in the representation of moist processes associated with (organized) convective and baroclinic flows; and improving the treatment of moist processes in ensemble forecasting techniques (e.g. extending the use of moist singular vectors).

AMMA and aspects of tropical-extratropical interactions

The West African monsoon (WAM) involves a wide range of interacting spatio-temporal scales, which are difficult to unravel from the available limited observational datasets. Indeed, weather and climate models continue to have difficulties in predicting its basic characteristics and associated rainfall. If we are to improve the predictability of the WAM, detailed studies of its fundamental processes are urgently required. A range of scientific challenges are associated with the predictability of weather systems on synoptic to convective scales. In particular, investigations are needed into rainfall and the role of moist processes in the African Easterly Jet - African Easterly Wave system, interactions between the Inter Tropical Convergence Zone and the Saharan heat low, impacts on the subtropical jet, and the occurrence of dry/wet spells.

Further challenges are related to the assessment of the utility of adaptive observations and the prospects for ensemble forecasting for West Africa. This involves assessing the appropriate initial perturbations and evaluating the skill and utility of ensemble forecasts for West Africa.

3.2 Data Assimilation and Observing Systems

New observations

Several observing systems and technologies are currently at the edge between research and operations. In other words, they seem to have a potential for operational use, but it is still a challenging task to integrate them as operational observing systems. A typical example is related to lidar observing systems. The wind lidar on the future ADM-AEOLUS satellite demonstration mission will produce wind profile information globally in real time. An airborne lidar has potential to provide targeted observations and to help validate the satellite data. This type of “observing system” is relevant to most of the European weather phenomena previously identified.

Improved use of observations in critical areas

For several weather phenomena (mid-latitude storms, PV-streamers, Mediterranean storms, …) one needs to observe and understand more precursors or key weather elements which often occur in cloudy areas known to be poorly sampled by satellite measurements. The use of satellite data should be extended in cloudy areas and over land and sea-ice. An optimal observing network and optimal data assimilation and observing strategy over the European seas and the Atlantic and Arctic oceans for these key regions should be developed.

Observation targeting for Europe

A Data Targeting System (DTS) has been developed in the project “Eurorisk Preview”. A one year trial of the DTS was carried out and a list of events compiled. Analysis of these events may offer more clues on the situations when targeting could offer some benefit. Using these events it is necessary to consider to what extent this DTS is applicable to the different types of European phenomena. The deployment of targeted observations should rely on the computation of some sensitivity fields but one still needs to improve the understanding of the strengths and weaknesses of current sensitivity computation methods, including the extension to longer time ranges (lead time around one week). Some parts of the in-situ observing networks could be also organised in a way which supports improved weather forecasts over Europe, for example by relying on some “sensitivity climatologies” derived by season or by weather regimes.

Optimal data assimilation

Current data assimilation systems are based on structure functions which are “optimal in a global statistical sense”, but not adequate for many sensitive areas affected by an atmospheric flow or weather features which are strongly anisotropic in space. Structure functions are close to isotropy in most of the operational data assimilation systems (although a 4D-VAR helps in producing more realistic structure functions) and the assimilation of observations is sub-optimal in many areas affected by strong jets, vertical wind-shears, high temperature gradients, etc.… In addition, operational NWP in Europe is characterized by a wide variety of data assimilation methodologies, which makes it more difficult to converge towards a general “European data assimilation and observing strategy”. However, operational NWP in Europe has now built a wide variety of numerical tools around the variational algorithms which are used in many forecasting centres. Furthermore, ensemble data assimilation techniques are being more widely used to document the “errors of the day” which can then be used in the data assimilation system.

Observation impacts

It would be valuable to identify which routine observations are useful for improving weather forecasts over Europe at medium range and beyond (day 5 to 14). Using the new adjoint sensitivity tools available might not be as relevant at this time range as for the shorter range, and innovative methods should be developed to be used together with the more traditional OSE approach. The European community might need to put more efforts into observing regions which are adjacent to Europe, such as Africa, the tropical Atlantic and polar regions. The data from all appropriate campaigns should be used to investigate this aspect (e.g. AMMA, IPY, T-PARC, T-NAWDEX).

Observing strategies for high-resolution NWP

The new generation of mesoscale models now operate at unprecedented resolution (1-4 km) and offer the potential for resolving convective and other small-scale motions and hence improving high-impact weather forecasts. New observational strategies are needed to provide accurate initial conditions on appropriate scales. In particular, weather radars offer high-resolution Doppler winds, cloud and precipitation microphysical properties, and even humidity from measurements of refractivity. GPS stations have already shown a slightly positive impact when the integrated water vapour content is assimilated, but the coverage might still be too sparse to get a major gain. Another approach might be to deploy a network of low-cost high-density ground-based meteorological sensors (e.g. tomographic GPS) communicating via mobile-phone technology. Another focus could be the assimilation of satellite water vapour radiances into the model and investigate the impact on cloud structures, initiation of convection and QPF. The imager and sounder instruments onboard the Meteosat Third Generation satellite could provide very relevant data to investigate this aspect. The main components of the Global Observing System (GOS) have been regularly assessed quantitatively through OSEs during the last 10 or 20 years. However OSEs on meso-scale observations (e.g. Doppler winds, radar reflectivity, GPS networks etc) are still in their infancy and some work is needed to build relevant OSES at these scales.

Data assimilation strategies for high resolution NWP

The models have to be run more frequently and more rapidly than at global scales, using the additional meso-scale information and without destroying the overall field consistency provided by the last run from the global data assimilation and forecasting system (necessary to provide at least lateral boundary conditions). This means that a good meso-scale data assimilation system has to cope with a wide range of scales from global down to the kilometre resolution. Studies indicate that the validity range of the tangent linear approximation in 4D-Var may be too short for meso-scale systems (e.g. moist convection). There is a need to address the lack of the traditional balance conditions at the convective scale, and to infer changes to model state variables such as wind and temperature from observations of cloud and precipitation. Such techniques might employ ensemble-based Kalman filters, to be adapted for this challenge, as well as other new ideas in data assimilation theory.

Improved surface fields

With increasing resolution in NWP models, the importance of the correct representation of the Earth's surface increases. For example more realistic characterisation of the soil moisture, vegetation state, surface skin temperature, snow and ice cover will lead to smaller biases in surface energy fluxes. A better representation of the surface can also increase the use of satellite sounding data over land areas. More work is needed on the data assimilation techniques related to surface observations (e.g. Extended Kalman Filter) and to assess their role on predictability.

3.3 Ensemble prediction and TIGGE

The THORPEX Interactive Grand Global Ensemble (TIGGE) is a framework for international collaboration in the development and testing of ensemble prediction systems. While European NWP centres contribute strongly to the provision of medium-range ensemble forecasts, Europe has a particular strength in limited area modelling that enables a strong contribution to TIGGE-LAM, the regional component of the TIGGE project.

Meteorological challenges

A basic challenge is forecasting the key types of meteorological phenomena that lead to high-impact weather affecting Europe. Clearly, it is important that these are represented as well as possible by the numerical weather prediction models used for ensemble forecasting. At the same time, the TIGGE data set is an invaluable resource for scientific studies of these phenomena.

Meteorological feature	Priority for TIGGE
Extra-tropical cyclones. Includes windstorms resulting from vigorous **Atlantic depressions** primarily affecting NW Europe. The formation and effects of **Mediterranean cyclones** is particularly important. There are also plenty of short-term forecasting issues associated with severe storms of small geographical extent. **Polar lows** are much smaller and more transient than regular mid-latitude depressions. However, they typically produce severe weather in the form of heavy precipitation, usually falling as snow, and strong surface winds.	1, for global and LAM
Dynamic QPF. Quantitative Precipitation Forecasts are important particularly for the prediction of flooding. The main emphasis for short-range forecasting is the prediction of **pluvial floods** – those related to localised strong rainfall events. While the modelling of **convection** is important in regional scale models, because of its importance to QPF, this is felt to be even more important for finer scale models. The effect of orography on rainfall is important also.	1, especially for LAM - including testing of the new generation of convection-permitting LAM ensembles
Influence of the tropics on the extratropics. The **extra-tropical transition of tropical cyclones** has an important influence on cyclonic development in the Atlantic sector. More generally, **Rossby wave trains** originating from the tropics bring storms to mid-latitudes. On a longer timescale, but still affecting the THORPEX two-week timeframe, improvements in the simulation of the tropical **Madden-Julian Oscillation** (MJO) should allow better forecasting of the effect of the tropics on mid-latitudes.	2, for global
Persistent weather patterns. The simulation of **blocking**, particularly in the North Atlantic is crucial to forecasting persistent weather patterns over Europe. Reliable forecasting of the maintenance and/or breakdown of blocks is a priority. The European meteorology of recent years has underlined the importance of being capable of predicting the onset and the lifetime of **heatwaves** (often linked with Euro-Atlantic blocking). Such phenomena have been shown to have sometimes extremely important societal impact. For medium-range forecasting, it is important to be able to capture persistent, larger-scale periods of wet weather (or periods of snow-melt) that could lead to **fluvial floods**	2, for global
Polar influences. The IPY and its component projects, such as GFDex, should help our understanding of high-latitude influences on mid-latitude weather systems.	3, for global

The table above sets out a range of meteorological phenomena which it is important for ensemble prediction systems to forecast well in order to predict high-impact weather in Europe. These reflect the issues in predictability and dynamical processes set out previously, but also highlight the requirements for numerical weather prediction on both medium- and short-range timescales. Here, 1 indicates the highest priority and 3 the lowest.

High-impact weather phenomena most relevant to the use of TIGGE forecasts in Europe; the right-hand column indicates the priorities for global medium-range ensembles and regional short-range ensembles.

Regional forecasting challenges

Thanks to the many regional modelling systems running operationally, and especially to the many initiatives in LAM EPS, Europe is in the best position to contribute to TIGGE LAM in a relatively short time. This should be even easier thanks to European cooperation within four modelling consortia and under the coordination of the SRNWP/EWGLAM programme. It is important to design a programme to use and optimally combine the regional models and LAM EPS that encompass a large part of Europe, and possibly the adjoining North Atlantic, with sufficient resolution to represent mesoscale features (i.e. a grid length of around 10 km or better).

Regional-scale multi-model techniques could be extended to very high-resolution (~1 km grid-length) models in the longer term. Even with likely improvements in computer technology over the next few years, we envisage that these higher resolution models will still be limited to the national level. In the mean time, research and development collaboration to develop methodologies for very high resolution ensembles should be encouraged. TIGGE LAM will also allow the coordination of scientific activities to develop and test the new generation of convection-permitting LAM EPS which represent the future of regional LAM ensembles.

In the short-range the impact of initial conditions is very large, and deterministic forecasts give reliable prediction of synoptic scale features. Beyond the limit of deterministic predictability, there is scope for probabilistic forecasts to highlight the likelihood of high-impact weather. There are number of scientific issues that arise from this approach, for example how best to verify probabilistic forecasts, or how many members are needed in an ensemble.

One of the key aspects of TIGGE is research into the benefits of multi-model ensembles; not only does this allow an economical way of forming a larger ensemble, but it also allows one to exploit the different strengths of different forecast models. For TIGGE LAM, scientific issues include aspects related to increasing the predictability at the local scale and to the interaction and competition between larger scale perturbations, given by the driving global systems, and "local" perturbations generated specifically for the LAM EPS.

The existence of TIGGE poses new opportunities and challenges for understanding fundamental questions in the context of ensemble forecasting. TIGGE enables research to address questions related to the importance of model error versus initial state error, and to investigate in detail the benefits and drawbacks of various methods for generating initial perturbations. It also holds the potential to look at properties of (very) large ensembles.

3.4 Societal and Economic Research and Applications

At the international level the World Weather Research Programme (WWRP) Societal and Economic Research and Applications Working Group (WWRP SERA Working Group) has, as one its tasks, the responsibility for the co-ordination of the assessment of the societal, economic and environmental benefits of improved forecasts for the THORPEX Programme. However, it is crucial that any European plan for THORPEX has SERA activities since most of the weather-related research and operational activity is motivated by socio-economic benefits to justify the financial investments that are made to improve weather predictions.

High impact weather

The primary purpose of the European plans for SERA is to undertake a number of societal and economic-related demonstration projects focused on high-impact weather and information.

Many discussions of the social and economic impact of weather tend to focus on extreme weather events, such as major storms, floods and heat waves. This is understandable as such weather extremes are highly visible to meteorologists and the public, as well as policy makers. It should be appreciated, however, that non-extreme "normal" weather can also have significant social and economic consequences. The impacts are often cumulative, being the result of many frequent occurrences as opposed to relatively rare extreme events. The definition of adverse weather is also highly user dependent: calm weather may have significant economic consequences for a nation with substantial wind energy production capacity, for example.

As well as the distinction between "severe" weather and "high impact" weather, there is also an important distinction between the socio-economic impact of weather and how much of the impact can be mitigated. Headline figures for losses – both in lives and money – associated with weather events are not equivalent to the losses that might be avoided with an improved forecast.

A small avoidable loss may mean that a high skill forecast of high impact weather may have little socio-economic benefit, whereas if the avoidable loss is considerable, then even a moderately skilful forecast could provide substantial benefits and be described as a "high impact forecast". As with high impact weather, the impact of forecasts can accumulate over frequent but unremarkable events or it may be associated with a single significant event. For example, relatively small errors in temperature forecasts result in large cumulative losses for the European energy sector.

Communication of uncertainty and probabilistic forecasting

The THORPEX programme is mainly concerned with the improvement of forecasts of high impact weather in the lead time range of 1 to 14 days ahead. Intrinsic limits to the predictability of the atmosphere at these lead times means that purely deterministic forecasts will not be sufficient and many, if not all, applications will be based on probabilistic forecasts, ensemble prediction being the main approach under consideration.

When it comes to public safety, most decision makers are not comfortable with probabilistic forecasts. This might be due to the fact that public decision makers are highly sensitive to false alarms, for strategic reasons, and at the same time express a strong need for a high detection rate, for obvious tactical reasons. From their experience both in weather forecasting and in assessing risks for particular users, forecasters are able to take into account specific needs, filter low probabilities for limiting false alarms, and highlight significant risks for improving detection. This results in an expert assessment that is neither purely deterministic nor really probabilistic, but that is likely to suit the requirements of decision makers better than a full set of probabilistic forecasts. To be able to provide this type of forecast optimally the forecaster must be aware of the risks to which the decision maker is exposed, and also the constraints under which they are operating.

Verification

In communicating forecasts, particularly for high impact weather, to customers it is important that forecast verification is considered part of the communication process. Verification approaches will have to be graded by the extent to which they are focused on the end user of the forecast and designed to be readily comprehensible by the general public. For forecasts of high impact weather it is essential that verification results should be presented alongside the forecasts so that users can readily understand the quality of the forecast they are currently using.

4. RESEARCH PRIORITIES AND ACTIONS

4.1 Predictability and Dynamical Processes

Synthesis of challenges

From the detailed list of challenges associated with the individual phenomena (section 3.1) the following overarching/priority challenges have been identified:

- To identify the processes responsible for Rossby wave triggering, propagation and breaking and quantify their relative importance.

- To assess the importance of interactions between systems of different scales and dynamical or geographical origins for predictability in the Atlantic-European sector:
  - Quantify relative importance of large-scale flow vs. local forcing for predictability (of e.g. Mediterranean cyclones, deep convection);
  - Assess importance of upscale cascade for predictability in the Atlantic-European sector (e.g. organized tropical convection, extratropical eddies;
  - Assess relative importance of tropical and extratropical components for predictability of downstream impact of ET.

- To quantify the role of diabatic processes for dynamics and predictability:
  - Assess their role in specific weather phenomena (e.g. extratropical cyclones, blocking, PV streamers, …);
  - Assess contribution of simple cloud schemes in cloud resolving numerical

weather prediction models to errors in quantitative precipitation forecasting;
    - Determine accuracy and importance of representation of boundary layer moisture and structure.

- To contribute to the development of the numerical model chain (including probabilistic prediction) and verification tools:

    - Identify situations leading to inconsistency in sequential forecasts and/or pronounced medium-range forecast busts;
    - Identify what determines the timescale on which model error becomes more important than initial condition error (which will presumably depend on both the model used and the weather conditions);
    - Investigate transferring large-scale predictability to the mesoscale via high-resolution modelling;
    - Determine the theoretical limitations of ensemble forecasts;
    - Investigate to what extent ensemble systems sample present uncertainty;
    - Assess trade-off between ensemble size and resolution, and between vertical and horizontal resolution.

- SERA-connection: Identify the relative importance of the factors influencing adaptive capacity at multiple scales and in response to multiple weather related hazards.

Recommended actions

Action 1: Continue to develop plans for an international field experiment **THORPEX North Atlantic Waveguide and Downstream impact EXperiment (T-NAWDEX)** in autumn 2012 or 2013, possibly in conjunction with HYMEX, to study the triggering of wave guide disturbances, their subsequent evolution over the North Atlantic and the associated downstream impacts over Europe, the Mediterranean and Northern Africa. The overarching scientific goal of T-NAWDEX is the detailed investigation of the physical processes that are primarily responsible for degradation in 1-7 day forecast skill in global prediction systems and of their representation in numerical weather prediction (NWP) models.

The potential triggering processes are the extratropical transition of tropical cyclones, intense extratropical cyclones in the western North Atlantic, polar stratospheric PV anomalies, and large-scale orographic forcing. The first of these processes (ET in the North Atlantic) has maximum frequency in September/October (on average about 5 events per year, but high variability), the second (intense extratropical cyclones) occurs most frequently in winter, but also in late autumn and the two other processes are expected to be equally likely in all seasons. During an autumn season it will be very likely that several potentially high-impact weather events occur over Europe whose predictability crucially depends upon adequate observations and modelling capabilities for the North Atlantic waveguide and its disturbances. These events include the breaking of Rossby waves (i.e. the formation of PV streamers and upper-level cut-offs), heavy precipitation (in particular to the south of the Alps), blocking over the eastern North Atlantic, Mediterranean cyclones and perhaps also long-range transport of Saharan dust towards Europe. Several of these phenomena will be studied intensively within the HYMEX field campaign that has a particular focus on mesoscale predictability, precipitation forecasts and hydrological applications in the Mediterranean region. T-NAWDEX would therefore be an ideal upstream component to complement HYMEX and, as in T-PARC, would address the trans-oceanic propagation of meteorological disturbances and its downstream impacts. Scheduled about four years after T-PARC, the proposed experiment will profit strongly from the experiences and results from T-PARC and will include observational strategies and facilities that have been developed in the meantime.

The first planning meeting of the THORPEX-North Atlantic Waveguide and Downstream Impact Experiment (T-NAWDEX) took place in Erding, Germany 19 - 20 February 2009 with participants from France, Germany, Israel, Switzerland, United Kingdom, and the U.S.A. The potential for using three research aircraft was discussed, specifically the United Kingdom

FAAM's BAE146, the German high-altitude long-range research aircraft HALO, and the U.S. High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) G-V aircraft. A pilot study for T-NAWDEX with the FAAM's BAE146 took place in November/December 2009. Further important components would be coordination with the operational hurricane field programme operated by the NOAA Atlantic Oceanographic and Meteorological Laboratory/ Hurricane Research Division (AOML/HRD) and strong satellite and modelling components.

It will be important to include a strong European (and potentially African) SERA component into T-NAWDEX (ideas to be developed).

Action 2: In addition to field experiments, it is vitally important to conduct national and/or international research programmes/projects that address specific scientific challenges (see list above) on the basis of:

- Diagnosis of operational analyses, deterministic and EPS forecasts (TIGGE);
- Idealized modelling and theoretical studies;
- Real case sensitivity studies.

Ideally, these projects should be performed by academic groupings interested in THORPEX in combination with representatives from the national weather services and/or ECMWF. They should address basic PDP research questions and, where possible, provide essential information for the planning and conduct of a T-NAWDEX campaign. The ERC should encourage different European consortia to prepare research proposals along these lines and provide a platform for the exchange of results.

Action 3: A special research project has been suggested by the SERA working group to investigate the meteorological sensitivity of selected economic/societal sectors. We would strongly welcome such a SERA/PDP pilot project. We envisage that the SERA group would, for the selected sectors, inform the PDP group of the relevant variables, the desired forecast-accuracy and lead times. The PDP contribution could quantify the existing forecasting capabilities (deterministic vs. probabilistic, global vs. mesoscale, medium vs. short-range), identify the relevant weather phenomena and make recommendations for improvements of the forecasting system.

Action 4: Organise a joint workshop between the PDP group and the WCRP Working Group on Numerical Experimentation (WGNE) to discuss the development and application of diagnostic techniques to understand the origin of forecast errors and thus aid model improvement.

Action 5: Discuss the linkage of European PDP activities with those of other regional THORPEX committees. Current priorities are (i) to work with the Asian and North American regional committees on utilizing the T-PARC observations and planning T-NAWDEX and (ii) to coordinate with the African Regional Committee in implementing the African THORPEX plan.

4.2 Data Assimilation and Observing Systems

Synthesis of challenges

The skill of medium range forecasts has been shown to rely heavily on the accuracy of the definition of the initial state of the atmosphere/surface. This is achieved through assimilation of observations from both in-situ and satellite platforms. Observing System Experiments (OSEs) at ECMWF and various other European NWP centres have shown the value of the different components of the observing system for both global and European scale models.

There have been several field campaigns in recent years to try and learn more about the impact of observations and possible benefits of targeting observation in sensitive areas over the Atlantic Ocean (e.g. ATReC, ASAP, PREVIEW DTS, E-TReC) and OSEs have been run to determine their impact. To date, any impacts of the additional targeted data in sensitive regions over the Atlantic have been small on average with 4D-Var assimilation employed. In spite of this, developments in the deployment and use of observations in the European region and assimilation techniques need to be fostered in order to provide improved forecasts of extreme weather events. There are still more benefits to be obtained from extending the use of current satellite datasets into cloudy areas and at low levels over land surfaces. New satellite datasets (e.g. ADM-AEOLUS, SMOS and ASCAT soil moisture) also potentially can provide significant gains in forecast skill over Europe but research needs to be done to demonstrate this.

For Europe, a major new challenge is the assimilation of dense observation networks (e.g. radar data, GPS total zenith delay, Meteosat satellite radiances) in mesocale (~1km) NWP models. This is still in its infancy but the benefits of high resolution NWP for forecasting localised severe weather events is already well proven and will be an increasing focus of activity.

In data assimilation, Europe faces issues at the kilometre scale, which determine details of high-impact weather, and larger scales which often control where and whether it will occur. Similarly we need to combine advanced "errors of the day" approaches which map the day to day variability in the structure of forecast errors with the advantages of the variational approach which allows effective use of high time and space-resolution satellite and radar observations. Practical computational issues mean that compromises must be sought. Within this framework we must assimilate all potentially useful observations; for instance work is needed on how to optimally use satellite information under all conditions (i.e. clouds, land and sea-ice).

In response to the issues given in section 3.2, a list of actions below have been formulated for the European Regional Committee to monitor pertaining to Observations and Data Assimilation.

Recommended actions

Although some of the challenges cannot be addressed by very precise actions, the following planned actions (for the next 5 or 7 years) should bring significant progress on many issues. They have been chosen because they would benefit from collaboration on a European scale, build on European expertise and address European needs, while remaining within the overall scope of THORPEX.

Action 1: **ECMWF, Météo-France and Met Office should report on the impact of ADM-AEOLUS data on global NWP to the Thorpex European Regional Committee, as soon as possible once the data are available. Other NWP centres are invited to collaborate on this action as soon as possible, considering the limited lifetime of the mission**. The lidar technology is currently the best example of observing system which requires a "significant push" towards operational meteorology. Specific actions like this one have not been identified for other instruments in this document: however several other new technologies may deserve a similar "push" (e.g. low frequency microwaves for soil moisture).

Action 2: **Encourage the EUMETNET programme OPERA to exchange in real time surface precipitation composites and 3D radar reflectivity data**. The assimilation of some information contained in these radar datasets is important in the development of NWP models at kilometre scales. Moreover the radar information may also be useful for larger scale models, including global. Current band-width limitations may limit the exchange of data in the short term.

Action 3: **Encourage further development of radar data assimilation** Efforts will be aimed at the full exploitation of multi-parameter radar for assimilation into high-resolution NWP models. Although precipitation is well observed by weather radar, attempts to assimilate radar reflectivity data have so far met with little success. New measurement and data assimilation techniques need to be developed which include (1) dual-polarization retrievals of rain-drop size and hail intensity; (2) refractivity measurements that provide information about humidity fields in the boundary layer; (3) Doppler radar winds, sometimes from more than one radar thus allowing all three wind components to be estimated. The assimilation of data from these sources, and, in particular, of Doppler winds from insects, and refractivities and polarimetric variables should lead to the model more accurately tracking developing convection before precipitation appears. The polarimetric variable, differential phase shift, is a path-integrated variable that is virtually unaffected by attenuation and hail, and thus provides new information in situations of heavy rain that will be particularly valuable for flood forecasting.

***Action 4**:* **Encourage improvements in surface-based observing networks in polar and tropical regions.** For the upper-air, AMDAR can be useful for the polar regions, and for the tropics both AMDAR and ASAP are useful. The experience gained in AMMA, and later IPY and T-PARC should be used to get recommendations for optimising the observing components in each region. Also EUCOS (and its sub-programmes E-ASAP and E-AMDAR) should consider longer forecast ranges in their observing system design (so far they have considered mainly the short-range forecasts, i.e; up to about day 3).

Action 5: **Encourage improvements in the use of satellite data in cloudy areas and over land, snow and sea-ice.** The assimilation of cloudy hyperspectral infrared radiances has recently started to take place at a few places in Europe. The exchange and comparison of information should be encouraged to progress in this direction. Similarly, more effort should be devoted to the assimilation of satellite radiances over land, snow and sea-ice. One could build on the experience gained during field campaigns such as AMMA and Concordiasi.

Action 6: **Develop data assimilation schemes for surface fields.** Snow mass and near-surface soil moisture are strongly coupled to the atmospheric circulation, and affect both droughts and floods. Both are poorly represented in NWP and climate models, and are hard to observe using surface-based techniques over large areas. Global satellite-based estimates of soil “wetness” and snow cover are now available and the assimilation of these datasets in NWP models should be pursued. Improved techniques for assimilation of observations in surface fields (e.g. Extended Kalman Filter) also need to be developed along with more complex land surface models.

***Action 7**:* **Develop data assimilation methodologies** in order to get a better understanding of which observations and sampling strategies will improve the forecasts. The new tools using the adjoint sensitivity techniques to identify the impact of individual observations types on the short range forecast should be developed further within Europe. These tools can inform the design of the future global and regional observing networks and reduce the need for OSEs which are expensive both in computer and human resources. Nevertheless a co-ordinated activity on OSEs in Europe especially for high resolution observing systems needs to be maintained.

Action 8: **Coordinate activities in Europe on research in data assimilation.** There are several themes for co-ordination of data assimilation at different scales:

- To bring the meso-scale data assimilation systems to the level of maturity of the present global systems;
- Investigate ensemble data assimilation for computing flow-dependent structure functions including involving the TIGGE group;
- Develop improved structure functions in sensitive areas.

These activities are now well underway in the main European NWP centres and the outcome of their results should be shared with the THORPEX DAOS community.

4.3 TIGGE – Global and Regional

Synthesis of challenges

The THORPEX Interactive Grand Global Ensemble (TIGGE) is a framework for international collaboration in the development and testing of ensemble prediction systems. At the time of writing, the global part of the TIGGE project is well underway and TIGGE-LAM, the regional component of TIGGE, after the first set-up period is now focussing on specific activities and writing down a more precise Strategic Plan. The main issues affecting TIGGE depend upon the relevant time and space scales, so throughout this section of the plan we have distinguished the different priorities for the global and regional parts of the TIGGE project.

Although TIGGE is a global project, there is strong potential to use the medium-range global ensembles to improve the prediction of high impact weather over Europe, especially for week 2 (8-14 days ahead). There is already a strong European involvement in the TIGGE project. ECMWF and the (UK) Met Office are providing output from their 15-day ensemble forecasts to the TIGGE database, and Météo-France is contributing short-range ensemble forecasts. ECMWF is also hosting one of the three TIGGE archive centres and the main TIGGE project website (http://tigge.ecmwf.int/).

The GIFS-TIGGE working group has agreed its scope should include applied research on ensemble forecasting, including:

- *A posteriori* calibration in all forms (bias correction, downscaling, etc.);
- Combination of ensembles produced by multiple models;
- Use of information in control forecasts;
- Research to support probabilistic forecast products.

Those aspects are all included in this plan, but we have also included more wide-ranging research encompassing more fundamental research on ensemble forecasting methods.

This section of the plan highlights actions which should be taken in a European context to facilitate the success of the global TIGGE medium-range forecasts and to realise the benefits of TIGGE and TIGGE-LAM for short-range regional forecasts.

Recommended Actions - to support TIGGE related activities

Action 1: **Develop improved versions of Numerical Weather Prediction models.** The development of improved numerical models underpins our ability to improve the skill of ensemble forecasts. The scientific understanding of the key meteorological phenomena is primarily the concern of the PDP area of THORPEX, but it is important that knowledge is fed through to the implementation of improvements in the numerical weather prediction models used for forecasting. While the THORPEX research programme does not formally include model development activities, these are carried out in conjunction with the joint WCRP/WWRP Working Group on Numerical Experimentation (WGNE).

The ongoing increases in limited area model resolution, for both deterministic and ensemble forecasting highlight the importance of establishing a broader long-term effort within the WWRP to focus on improving the skill of short-term regional forecasts. This means that discussions need to take place between the different groups with interests in this subject, including the TIGGE-LAM panel, the MWFR (Mesoscale Weather Forecasting Research) working group and the WGNE

Action 2: **Establish infrastructure for the exchange of ensemble forecast data.** Three global archive centres (ECMWF, NCAR and CMA) have been established to hold the global TIGGE database. The necessary infrastructure has been set up to transfer ensemble forecast data from the TIGGE data providers to the archive centres, and to make the data available to the research community.

The infrastructure to exchange regional ensemble forecast data requires more development. Europe can give a very important contribution to the standardization of data exchange thanks to the ongoing SRNWP Interoperability Programme started in late 2008 under the leadership of the Met Office. Strong links between the Interoperability Programme and TIGGE LAM have already been established. This should facilitate the exchange of TIGGE LAM data and products.

During the first phase of TIGGE-LAM, it was decided to implement regional archives of “high-priority” (HP) parameters, i.e. those parameters that are widely used in regional forecasting. A list of TIGGE LAM output parameters was defined and it was agreed that the HP subset would be included in regional archives hosted by the three TIGGE archiving centres following a geographical competence principle, i.e., data from European LAM EPSs will be archived at ECMWF. It is envisaged that the archiving of the full set of parameters will be planned and implemented in coordination with GIFS-TIGGE working group in conjunction with the development of the GIFS.

Standards to code and archive these parameters have been defined. They will be interpolated on a standard geographical lat/lon grid at 0,1° resolution and encoded in GRIB2. Higher resolutions will be adopted in the future for data from very the high resolution ensembles now being planned.

In order to stimulate scientific investigations and the work of the users (e.g. hydrologists), it was agreed to make the access to these data and products as easy as possible for who are not familiar with the tools and the methods used to manage meteorological fields. The use of common standards and tools is particularly important if dealing with the output of several LAM EPS systems.

Funding should be secured to support the development of this infrastructure and implementation of the European TIGGE-LAM.

Action 3: **Contribute ensemble forecasts to the TIGGE database.** All European Met Services which run global medium-range ensemble forecasts should add their forecast data to the TIGGE database, following the standards defined by the GIFS-TIGGE working group. At present, ECMWF, UK Met Office and Météo-France contribute global forecasts.

The global TIGGE project is now in a mature stage with data providers sending their data to three global archive centres (ECMWF, NCAR and CMA). The data are stored using archiving systems already available at those centres.

Once the required infrastructure is established for the exchange of TIGGE data, all European Met Services running regional ensemble forecasts should archive the agreed high priority parameters at ECMWF.

Action 4: **Develop data access agreements to support TIGGE and GIFS.** The global TIGGE data providers have agreed to make ensemble forecast data available to the research community, after a 48 hour delay. TIGGE-LAM data providers need to complete similar agreements. It is proposed to make the TIGGE-LAM data available for research with a reduction of the delay to 24 hours for regional data.

TIGGE data providers should develop data access agreements that will allow the GIFS development project to proceed. The global TIGGE data provides the basis of research and development leading to a future THORPEX Global Interactive Forecast System (GIFS). The aim of the GIFS is to use THORPEX research to implement improvements to operational weather forecasting. To this end, it is proposed to establish a GIFS Development Project to deliver prototype products, initially to assist in forecasting tropical cyclones, and later high-impact precipitation and strong winds. To take advantage of existing and planned infrastructure and experience, wherever possible, the GIFS development project will be carried out in conjunction with the WMO CBS Severe Weather Forecast Demonstration Project (SWFDP) and other WWRP forecast demonstration projects. The data policy for TIGGE LAM products for the GIFS should be evaluated and decided in a later stage.

Action 5: **Establish a European data set for objective verification.** For the evaluation of mesoscale deterministic and ensemble forecasts over Europe, it would be invaluable to have a data set of high resolution meteorological parameters suitable to perform statistically significant verifications. From the technical point of view, this could be compiled using the many high density regional networks already in place but not disseminated through the GTS.

Due to European data policies it is difficult to have access to these data; initiatives to produce high resolution analyses should be stimulated and supported by THORPEX in liaison with EUMETNET and particularly with the SRNWP (a programme on verification is ongoing under the leadership of the Met Office). Analyses based on these data have already been performed (e.g. by ECMWF and by the University of Wien) but only for limited periods during Scientific Projects or with strong access restrictions.

It is important to call the attention to the importance of this action. The availability of the TIGGE and TIGGE LAM archive at ECMWF, along with suitable observational data set or high resolution analyses at European scale (particularly precipitation) and the adoption of common methodologies for verification would accelerate research, and enable conclusive results based on high quality data and tools. Verification methodologies should follow the guidelines from the Joint Working Group on Verification.

***Action 6:* Coordinate regional ensemble forecasting initiatives across Europe.** Ongoing coordination of LAM EPS activities should be carried out under the auspices of the SRNWP, and its specific programme on cooperation on ensemble forecasting that is under development at the time of writing. This includes the establishment of collaborations to develop methodologies for higher resolution (kilometre scale) ensemble forecasting.

The participation of European groups involved in ensemble forecasting in Research & Development Projects (RDPs) and Forecast Demonstration Project (FDPs) is also encouraged.

This action, and all the other actions in this section need to take place in close collaboration with SRNWP and EWGLAM, which represents the European Met Services' interests in development of short-range numerical weather prediction.

Recommended Actions - Research and development actions on Ensemble forecasting

There are several scientific and technical issues that should be addressed within the TIGGE project to improve the use of ensemble forecasts. In this section we highlight several areas where research and development actions are needed. Priorities are given in brackets, indicating whether they are particularly relevant to either global / medium-range or regional / short-range ensemble forecasting. Here, 1 indicates the highest priority and 3 the lowest.

***Action 7:* Develop initial perturbation methods (1, especially for LAM).** Currently most LAM EPS systems rely solely on global EPSs to generate initial condition (IC) perturbations. Methods to generate perturbations in the ICs specifically for LAMs should be developed (ETKF or others), bearing in mind the need to maintain consistency with the boundary conditions derived from global models. Methods developed for a given LAM ensemble should aim at fully accounting for the IC uncertainty typical of that particular system. At present, several methods are in use to generate initial perturbations for global ensemble forecasts, e.g. singular vectors, error breeding and the Ensemble Transform Kalman Filter. Further research work is needed to ensure that the perturbations capture the uncertainties in the initial conditions as well as possible, including reasonable geographical variations of amplitude.

***Action 8:* Investigate and define the requirements for ensemble forecasting that come from data assimilation (1. global and LAM).** The link between data assimilation and ensemble forecasting is developing very fast, particularly in the global NWP community. Ensemble data assimilation techniques are becoming competitive with variational techniques in both cost and performance. One key issue is how well the ensemble perturbations represent the short-term forecast error covariances (both in terms of magnitude and spatial covariance structure).

The links between ensembles and data assimilation must also be exploited at the regional scale where, especially at the few km scale and below, data assimilation is still a big challenge because of unknown model error structures and to the absence of dynamical balances.

***Action 9:* Develop *a posteriori* calibration methods to correct forecast errors (1, global and LAM).** Numerical models generally exhibit errors that lead to biases in forecast fields or systematic errors in the ensemble spread. Research is needed on the best ways to correct these biases; for example, forecasts of past cases can be used to estimate “climatological” biases. More sophisticated techniques need to be developed to take good account of flow-dependent biases. One approach is to use a large “reforecast” data set (hindcasts of a large number of cases using an up to date forecast model) to estimate biases that depend on the large-scale circulation (e.g. grosswetterlagen). Calibration methods should also be developed to improve the downscaling of coarse resolution forecasts to finer scales, or specific locations.

Action 10: **Optimise use of information in control forecast. (1, global and LAM).** Most operational ensemble forecast systems consist of a control forecast, whose initial conditions are taken from an analysis, and a set of forecasts in which perturbations have been added to the initial analysis conditions. The ensemble is designed so that the ensemble spread should correspond to the expected forecast error. It follows that the errors in the control forecast are significantly less than the errors in the perturbation forecasts in the early part of the forecast range (although the skill levels become more similar as the forecast progresses). A particular question is how best to use the additional information in the control forecast, e.g., for the best estimates of forecast probabilities.

Action 11: **Develop methods for multi-model combination and assess the benefits (1, global and LAM).** Recent research has indicated that forecast skill is improved by combining ensembles from several different forecast models. This action is fundamental to the rationale of the TIGGE project. When combining forecasts from multiple models, differing biases (both mean and higher order moment errors) need to be accounted for by calibrating the individual forecasts before combining them, as described above. One issue is how best to weight the different ensembles; a balance needs too be struck between using a simple weighting approach and any benefit from a more complex and costly combination method. Work is also needed to determine the best way of accounting for inter- as well as intra-ensemble variability.

To an extent, the multi-model technique is beneficial because different models have different types of systematic errors. The degree of benefit is likely to depend significantly on methods used to combine forecasts from different models.

Action 12: **Clarify the relationship between spread and skill (1, global and LAM).** The common perception is that a high ensemble spread corresponds to a low confidence forecast, and low spread to high skill. This may be true if the ensemble spread is well related to errors in initial condition and model error. But it would not be true if, for example, errors in the initial conditions or model formulation errors are not captured by perturbations. So, this issue is related to the representation of both initial condition errors and model errors and it is of particular importance in regional modelling and for smaller scales. For such scales the very existence of the spread-skill relationship is sometimes questioned, in particular as far as rainfall and near-surface parameters are concerned.

Action 13: **Determine optimal use of resources (1 for LAM).** In a multi-model LAM environment the problem of trade-off between resolution and area integration (to allow for limited area overlaps) is a concrete one. For a given cost, forecast centres could either run a single-model ensemble for the most relevant domain to their users or a multi-model ensemble for a larger domain of relevance to several forecast centres. We need to compare the performance of lower-resolution multi model ensembles with higher-resolution single model ensembles. Severe events, however, will probably always require resolution higher than a given threshold. The speed, and ease, of data exchange is also a particular factor for short-range forecasting. There are several of factors that need to be balanced when deciding the best approach, including:

- Model resolution;
- Domain size;
- Number of ensemble members;
- Benefits from use of multi-model ensembles;
- Timeliness of data exchange.

Action 14: **Assess the optimum number of ensemble members (2, global and LAM).** A more general issue is how many members are needed in an ensemble forecast. This is likely to depend on the context: in order to get a good estimate of the most likely forecast a relatively small ensemble may be sufficient, but to get a good estimate of the forecast PDF a larger ensemble will be needed. In a multi-model ensemble context, fewer members would be needed from each contributing ensemble. On the other hand, a much larger sized ensemble will be needed where the ensemble is used to estimate forecast error covariances for data assimilation applications.

Action 15: **Develop methods for extreme event probability estimation and verification (1, global and LAM).** Much of the high-impact weather that THORPEX focuses on is fortunately rare. There is a problem of calibrating rarer events, i.e. relating forecast probabilities to actual outcomes. Consideration should be also given to the problem that it may turn out to be impossible to satisfactorily verify forecasts of really rare events.

Action 16: **Develop user-oriented verification of non-extreme events (2, global and LAM).** For many users, non-extreme events are more important than extreme events, not least because they are more common. For example, forecasts of temperature and winds affect forward energy prices. Such events will be easier to verify reliably than extreme events, but work is required to develop verification methods that are better related to socio-economic costs to users.

Action 17: **Develop stochastic physical parameterizations (2, especially for global).** As mentioned above, part of the benefit of multi-model ensembles is to allow for model errors by combining forecasts from several models with different types of model error. Stochastic physics schemes also attempt to account for model errors by adding in random variations that “target” uncertain aspects of the physical parameterizations. At the moment, stochastic physics schemes are rather crude. Further work is needed to develop stochastic physics schemes that are better at representing model errors.

Action 18: **Research ensemble forecast techniques for convective time- and space-scales (2, LAM).** TIGGE, and especially its regional-component counterpart TIGGE-LAM, should be used to assess the development of ensemble forecast techniques that are appropriate for convective time- and space-scales. Such techniques are acquiring increasing importance as NWP models operate on such shorter scales. These developments lead to new challenges for ensemble techniques that have been developed for and used successfully at synoptic scales.

Action 19: **Develop techniques for forecasting probabilities of weather parameters such as fog (2, especially for LAM).** The problem of deriving probability forecasts for derived parameters such as fog, visibility, cloud types and height, etc., needs to be considered. This is also an issue for near surface parameters such as soil temperature, soil moisture content, 2m T and RH for further hydrological modelling.

Action 20: **Compare results from different ensembles (2, global and LAM).** The TIGGE and TIGGE-LAM databases facilitate comparison between different ensemble prediction systems (e.g., relative performance for specific processes such as blocking on the synoptic scale or convective processes on the small scale). This information can be used to inform developers of each EPS to enable them to address specific shortcomings.

Action 21: **Coupling with applications: Air Quality, Hydrology (2, Global and LAM).** Thanks to the always increasing resolution of both GLOBAL and LAM models, coupled chains started to be developed to extend the improvement in numerical weather prediction also to other companion sectors like air quality and hydrology. These important applications are having an important feeback on meteorological community since they require higher skills especially as regards timing and localization of meteorological phenomena. The probabilistic approach should be further extended to these coupled chains.

Action 22: **Participate in research initiatives outside Europe to asses the performance of European LAM EPS in forecasting different type of Severe/High Impact Weather Events (3, LAM).** These R&D actions will give a very important contribution to the development of Regional Ensemble systems in other regions (like Africa) and will allow a very positive transfer of know-how and technology form Europe to the developing countries. This activity must be coordinated with the WG on MWFR and the WGNE since regional models must be adapted and optimized to best represent the specific weather events and to reduce model biases.

Recommended Actions - application of TIGGE data for research on predictability

The TIGGE data set is a major resource for research on atmospheric predictability. Two specific actions have been identified:

Action 23: **TIGGE should be directly exploited for research on the extratropical predictability of various atmospheric phenomena in the troposphere (1, especially for global).** Such research concerning, for example, a reassessment of error-growth rates for various variables, might initially focus on the extratropics (to be subsequently extended to other areas) due to the extratropics-emphasizing nature of models that presently provide TIGGE products. This research will also be highly useful in its relation to data assimilation offering a unique capability to study (amongst other things) analysis and model errors. Insights into analysis and model errors will also guide future OSE/OSSE relevant research. It needs, however, to be recognized in that context that the models used to create TIGGE may suffer from very similar errors (as they may share similar resolutions, and parameterisations may have been tuned for similar measures of error), so models might be more similar to each other than any one of them to the atmosphere. Consequently, model-generated ensembles from different centres may carry less information on model error, but could be dominated by the different methods used to estimate initial condition error structures. TIGGE also offers a wide scope to address the manner in which existing ensemble members should be weighted or recombined to span the range of atmospheric outcomes, acknowledging initial condition and model error.

Action 24: **TIGGE should be exploited to examine the predictability of the flow in the lower stratosphere given current medium-range models (2, global).** It should also be used to examine changes to atmospheric predictability during the occurrence of large stratospheric disturbances. At present only limited stratospheric data, on one level and with one diagnostic, is available through TIGGE, making this activity more challenging.

Recommended Actions - Research and Development for GIFS

There is general need for research to support the development of products focused on the prediction of high-impact weather events. The GIFS-TIGGE working group has established two technical focus groups: one focused on IT aspects of data exchange and the second on product development. The aim of the focus groups is to facilitate international collaboration between developers working in these two broad areas. The following actions have been specifically highlighted:

Action 25: **Develop intelligent diagnostics (2, global and LAM).** Ensemble forecasts produce a vast amount of data, which is hard for forecasters and end-users to interpret. To make the best use of the output, a suite of “intelligent diagnostics” needs to be developed to contribute to GIFS. For example, the ensemble forecast output can be automatically analysed to characterise features including extra-tropical cyclones and fronts (see Fig. 1). By combining this with tracking software, forecasters can be shown how different features are likely to develop over a period of several days. Another approach is to characterise the large-scale circulation patterns. Figure 2 illustrates a forecast of objective “Grosswetterlagen” patterns from the Met Office ensemble (this analysis method was developed with support from COST733). Further diagnostics should be developed, perhaps aimed at specific user groups.

Action 26: **Develop products for forecasting tropical cyclones (2, global).** Tropical Cyclones are the initial focus of the GIFS-FDP. While Europe is not directly affected by tropical cyclones, extra-tropical transition of cyclones can significantly reduce forecast skill over Europe.

A particular emphasis is on the development of products based on tropical cyclone forecasts that are exchanged by TIGGE data providers using the Cyclone XML (CXML) format initially developed for T-PARC.

***Action 27:* Develop products to improve the prediction of high-impact precipitation (2 global and LAM).** Precipitation is the second planned focus of GIFS-FDP. Research and development is needed on the best way to combine precipitation forecasts from multiple ensembles, and to evaluate the benefit of products based on those combined data. To underpin this initiative, a high-resolution precipitation data set for Europe would greatly facilitate the calibration of the ensemble precipitation forecasts for product generation and the subsequent verification of the products (see action 5).

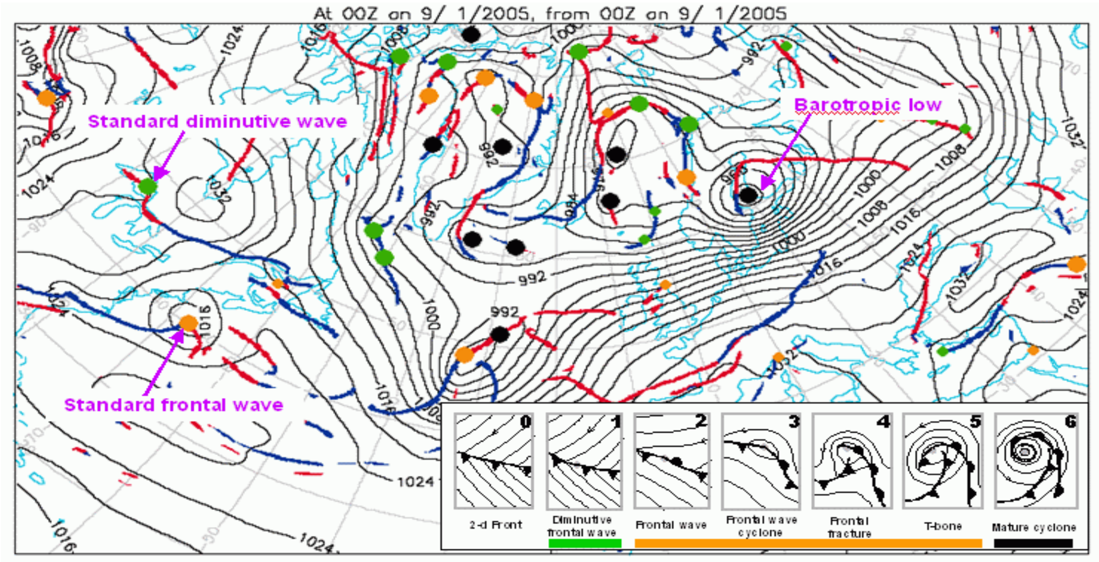
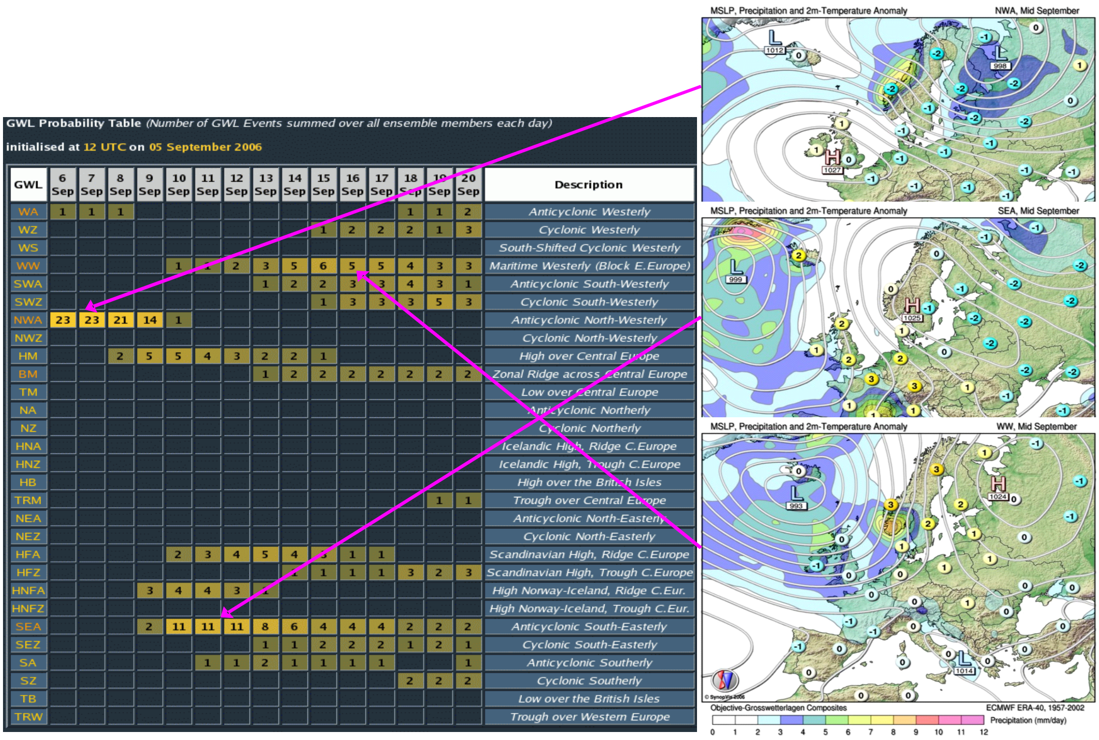


Figure 1 - Example of objectively identified fronts and cyclonic features, based on ECMWF EPS data from 0UTC on 9th January 2005. The different colours marking cyclonic features indicate different stages in their life-cycle, as shown in the inset



GWL Probability Table *(Number of GWL Events summed over all ensemble members each day)*

initialised at 12 UTC on 05 September 2006

GWL	6 Sep	7 Sep	8 Sep	9 Sep	10 Sep	11 Sep	12 Sep	13 Sep	14 Sep	15 Sep	16 Sep	17 Sep	18 Sep	19 Sep	20 Sep	Description
WA	1	1	1										1	1	2	Anticyclonic Westerly
WZ										1	2	2	2	1	3	Cyclonic Westerly
WS																South-Shifted Cyclonic Westerly
WW					1	1	2	3	5	6	5	5	4	3	3	Maritime Westerly (Block E.Europe)
SWA								1	2	2	3	3	4	3	1	Anticyclonic South-Westerly
SWZ										1	3	3	3	5	3	Cyclonic South-Westerly
NWA	23	23	21	14	1											Anticyclonic North-Westerly
NWZ																Cyclonic North-Westerly
HM			2	5	5	4	3	2	2	1						High over Central Europe
BM								1	2	2	2	2	2	2	2	Zonal Ridge across Central Europe
TM																Low over Central Europe
NA																Anticyclonic Northerly
NZ																Cyclonic Northerly
HNA																Icelandic High, Ridge C.Europe
HNZ																Icelandic High, Trough C.Europe
HB																High over the British Isles
TRM														1	1	Trough over Central Europe
NEA																Anticyclonic North-Easterly
NEZ																Cyclonic North-Easterly
HFA					2	3	4	5	4	3	1	1				Scandinavian High, Ridge C.Europe
HFZ									1	1	1	1	3	2	3	Scandinavian High, Trough C.Europe
HNFA				3	4	4	3	1								High Norway-Iceland, Ridge C.Eur.
HNFZ																High Norway-Iceland, Trough C.Eur.
SEA				2	11	11	11	8	6	4	4	4	2	2	2	Anticyclonic South-Easterly
SEZ								1	1	2	2	2	1	2	1	Cyclonic South-Easterly
SA						1	1	2	1	1	1	1			1	Anticyclonic Southerly
SZ													2	2	2	Cyclonic Southerly
TB																Low over the British Isles
TRW																Trough over Western Europe

Figure 2 - Example of objective identification of large-scale circulation patterns (Grosswetterlagen) from the Met Office medium-range ensemble forecasts

4.4 Societal and Economic Research and Applications

Synthesis of challenges

The European SERA plans will be focused on collaborative research to address the priorities established by the international WWRP/SERA Working Group namely:

- Estimation of the economic (societal) value of weather information;
- Understanding the use of weather information in decision making;
- Communication of weather uncertainty;
- Development of user-relevant verification methods;
- Development of decision support systems and tools.

Recommended Actions

Action 1: Contribute to basic inventory of SERA projects and the international web resource for social scientists and users that is being prepared by the WWRP/SERA Working Group

Action 2: Undertake a project, in collaboration with the European TIGGE community, to demonstrate improvements in the communication of uncertainty in weather forecasts. Such a project could use, when it is available, the SERA-friendly TIGGE data set that WWRP/SERA Working Group proposes should be developed.

Action 3: Contribute to the multi-year assessment, planned by the WWRP/SERA Working Group, of the global societal economic benefits (and costs) of weather information.

Action 4: The CAS decision to establish a sub-seasonal to seasonal prediction project provides the European THORPEX community the opportunity to develop systems to estimate the usefulness of longer time-scale forecasts of crop yield and the impact of weather on health. Crop yield predictions, for example, turn time series of weather into a socio-economic commodity that can be measured. Crop yield, and skill in its prediction, is therefore a useful metric for looking at weather impacts. Work on this is at an advanced stage and could form an integral part of the proposed SERA/PDP pilot project. The broader challenges involved in this work include the need for training in multi-disciplinary science and in the use of probabilistic forecasts; careful choice of methods to minimise and quantify uncertainty; and an awareness of how computer power can be most efficiently and synergistically used across projects.

5. ORGANISATION AND COOPERATION

The European Regional Committee has not operated as envisaged by the THORPEX Implementation Plan. However, the European operational and academic communities are very active in THORPEX research. Thus the main priority of the European Regional Committee is to promote the exchange of information between the different activities and thus facilitate progress on the actions detailed in this plan.

The main responsibilities of the European Regional Committee are:

- To plan a rolling series of biennial European THORPEX Workshops which provide a forum for reporting on progress and plans;
- To advise the THORPEX management on European priorities as needed; and
- To provide the annual report on European THORPEX activities to the ICSC.

In order to be effective, the committee membership should represent the THORPEX PDP, DAOS and TIGGE working groups, strengthen the links to the European national and international institutions, (ECMWF, EUMETSAT, EUMETNET / EUCOS, SRNWP, WGNE) as well as linking to the WWRP / SERA. The committee chair will be the contact point to the other Regional Committees.

The committee will communicate via email and meet at the biennial European workshops. The THORPEX European plan will be published on the THORPEX website and will be regarded as an evolving document which will be updated as necessary, but especially in conjunction with the European workshops.

ANNEX

WEATHER PHENOMENA OF RELEVANCE TO THE EUROPEAN COMMUNITY

In this section more detail is given of the weather phenomena and their impacts summarised in section 2. For the convenience of the reader the table from section 2 is reproduced below.

High-Impact Weather Phenomena	Specific scientific challenges	Frequency Time scales	Potential Societal and Economic Impacts
Blocking	• Quantify predictability of and understand processes responsible for onset, maintenance and breakdown. Identify precursors to blocking • Relate blocking to low-frequency (sub-seasonal to interannual) variability	Freq: av. <10% 5-14 days or longer	Heat waves, cold spells, droughts, air quality, forest fires, crop losses, water resources, power supply
Extratropical cyclones	• Assess role of upper-level anomalies • Investigate sensitivity in low and mid-troposphere.. • Quantify role of moisture and surface fluxes • Reduce errors in initial conditions	1/week 2-4 days	Wind, precipitation / floods, snow and ice, disruption to ground and air traffic
Polar weather (polar lows, arctic fronts)	• Enhance understanding of processes/ predictability • Improve representation of convection/snow fall, surface fluxes, clouds, PBL • Identify role of interaction with upper-level features	1-3 days	Snow, ice, strong winds
Mediterranean cyclones	• Quantify contributions to cyclogenesis from orography, strong surface fluxes, mesoscale upper-level structures • Identify which factors determine their (small) size and their track • Investigate development of tropical-cyclone-like systems and relate to polar lows	1/week (winter) 1/month (summer) 1-3 days	Precipitation, wind
Deep mid-latitude convection	• Quantify factors that determine timing and organization: relative influence of forcing factors, relative influence of synoptic-scale and local factors • Assess realism of mesoscale / high-resolution forecasts • Identify role in predictability of parametrizations vs. explicit convection • Utilise results of COPS, D-PHASE, E-TReC	Time scales >=1day	Lightning, hail, heavy precipitation, wind
Orographic flow systems (tip jets, föhn, bora, mistral, mountain waves)	• Quantify predictability related to upper-level features, air-sea / air-surface interaction, upscale effects, mountain waves, small-scale structures, interaction with cold-air pools and valley flows • Inclusion of sub-grid scale orographic information in models • Data assimilation in mountainous regions	1-3 days	Wind, (forest) fires, air safety, air quality (in the presence of local cold-air pools)
Upper-level forcing: PV Streamers and Rossby-wave breaking	• Accurate representation of wave-mean flow interaction • Quantify relative importance of different conditions (ambient, local transient, orography) • Prediction of evolution of PV streamer (mesoscale, interactions with surface, structure)	1/week 2-4 days	(heavy) precipitation, Foehn, dust/air quality, convection, floods
Upper-level forcing: cut off low systems	• Represent evolution and structure in NWP systems • Predict interaction between cut-off low / convection and resulting precipitation distribution • Quantify troposphere - stratosphere exchange • Assess mechanisms responsible for low predictability	1 / two weeks (summer) 1 / month (winter)	Severe convection, floods, extreme precipitation in centre when over warm sea

High-Impact Weather Phenomena	Specific scientific challenges	Frequency Time scales	Potential Societal and Economic Impacts
Structure and dynamics of boundary layer	• Improve modelling and utilise observations of boundary layer processes • Enhance understanding of these processes • Investigate representation and role of BL moisture	1-3 days	Rotors over airports, pollution levels in cities, initiation of severe convection, heavy precipitation along the Alps
Tropical influences: downstream impact of ET	• Quantify relative roles of tropical and extratropical perturbations as sources of uncertainty • Assess factors that control Rossby wave triggering: importance of TC structure, interaction with jet • Determine importance of physical parameterizations	Average 5ET /yr in Atlantic 3 days to 2 weeks	Increased uncertainties in forecasts (wind, precipitation), floods
Tropical influences: organized tropical convection & MJO	• Quantify impact on midlatitude predictability over Europe, upscale effects	14 days 6h – 2 days (tropical prediction)	Potential increase in predictability
Tropical influences: West African Monsoon	• Quantify importance of West African Monsoon as source of moist tropical air • Determine influence of modulation of subtropical jet	3-14 days	Predictability of midlatitude cyclones, tropical cyclogenesis, dust events
Polar influences	• Sparse data, strong orographic and surface forcings	3-14 days or longer	Influence on predictability
Heat Lows	• Quantify interaction of surface forcing and synoptic environment • Assess importance of West African heat low for European predictability	3-7 days	Heat waves, wind, midlevel intrusions such as the 'Spanish plume'.

Blocking

Prolonged episodes of extreme weather events such as droughts, floods, and heat waves are of considerable importance to society. One feature that is often implicated in these events is the persistent anticyclonic flow anomaly, often referred to as an atmospheric blocking episode, where the zonal flow is interrupted by strong and persisting meridional flow. The normal eastward progression of synoptic disturbances is obstructed, leading to anomalous storm tracks (Trigo et al., 2004). Since a single blocked situation can persist up to several weeks, they are an important component of intraseasonal variability, with just a few blocking episodes being able to determine the climate characteristics of one winter.

Most Northern Hemisphere blocking is seen to occur in the Euro-Atlantic sector (Pelly and Hoskins, 2003a; Barriopedro et al., 2006; Croci-Maspoli et al., 2007) and have a major impact upon European weather (Rex, 1950). Recent works have evaluated the impact of blocking episodes on both the precipitation and temperature fields of the Mediterranean Region (Quadrelli et al., 2001; Trigo et al., 2004).The frequency of blocking events over Europe presents a marked seasonal cycle with higher values in winter and spring (Tibaldi et al., 1997; Trigo et al., 2004). Blocking episodes usually last between 5 and 20 days, but their fingerprint is sufficiently intense to be noticed at the monthly scale (Quadrelli et al., 2001). The most important feature corresponds to the intensification of the meridional component of the mid-troposphere circulation that is perfectly visible during blocked situations, up and downstream of the British Isles. This configuration is usually associated with the split of the jet stream in two distinct branches, a feature that is widely accepted as a trademark of European blocking episodes (Rex, 1950). The impact of these events for the low tropospheric temperature field at 850 hPa extends from Iberia to the Black Sea with the most intense values being observed over the Balkans.

For these blocking events, forecasting skill in numerical weather prediction (NWP) models is usually quite poor beyond a few days, principally in predicting the transition to a blocked state (Tibaldi et al., 1997). A recent important contribution to the tools for medium-range forecasting has been the capability of producing an ensemble of probabilistic forecasts beyond the limit of deterministic predictability, which take some account of the uncertainties in initial conditions. The last generation of ensemble predictions has been able to produce relative skilful probabilistic forecasts of blocking with a lead time of up to 8-10 days (e.g. Pelly and Hoskins, 2003b).

More generally, the mechanisms involved in the dynamics of blocking are complex and imply a range of time-scales. As a consequence, very little is known about the processes responsible for the onset, maintenance and breakdown of blocking events and no precursors have been clearly identified.

The relation of blocking events to low frequency (subseasonal to interannual) variability is also a major unknown. The lack of studies addressing the climatic variability of blocking is reflected in the ability of General Circulation Models (GCMs) to simulate blocking. A finding common to most studies is an underestimation of the observed blocking activity and a lack in the frequency of long-lived blocks, strongly influenced by some systematic model deficiencies (excessive zonal flows, underestimation of low-frequency planetary waves) (D'Andrea et al., 1998). However, recently, there has been a renewed interest in the study of interannual blocking variability. Different studies have pointed out a significant relationship between blocking and regional modes of low-frequency variability. Focusing in the Euro-Atlantic area, the NAO has been shown the main teleconnection related-pattern over the Atlantic Ocean (Shabbar et al., 2001; Barriopedro et al., 2006; Scherrer et al., 2006), while other secondary modes may be more linked with European blocking (Barriopedro et al., 2006; Scherrer et al., 2006). Regional decreases during the last decades in Euro-Atlantic blocking activity have also been identified (Barriopedro et al., 2006) and supported in subsequent studies (Croci-Maspoli et al., 2007). In addition, thermal surface variables of long-term memory such as the snow cover have been proposed as firm contributors of the interannual variability of regional blocking, feasible candidates to the recent observed trends and useful seasonal predictors of the winter Atlantic blocking activity (García-Herrera and Barriopedro, 2006), suggesting that a correct parametrization of land-surface processes may be a key factor to improve blocking simulations in GCMs.

Barriopedro, D., R. Garc´ıa-Herrera, A. Lupo and E. Hernandez, 2006: A Climatology of Northern Hemisphere Blocking. Journal of Climate, 19, 1042-1063.

Croci-Maspoli, M, C. Schwierz, and H.C. Davies, 2007: A multifaceted climatology of atmospheric blocking and its recent linear trend. J. Clim., 633—649.

D'Andrea and co-authors, 1998: Northern Hemisphere atmospheric blocking as simulated by 15 atmospheric general circulation models in the period 1979-1988. Clim. Dyn., 14, 385-407.

García-Herrera R. and D. Barriopedro, 2006: Northern hemisphere snow cover and atmospheric blocking variability. J. Geophys. Res. 111, D21104, doi:10.1029/2005JD006975.

Pelly, J.L., and B.J. Hoskins, 2003a: A new perspective on blocking. J. Atmos. Sci., 60, 743--755.

Pelly J. and B. Hoskins B., 2003b: How well does the ECMWF Ensemble Prediction System predict blocking?. Quart. J. Roy. Meteor. Soc., 129, 1683-1702.

Quadrelli, R., V. Pavan and F. Molteni, 2001, Wintertime variability of Mediterranean precipitation and its links with large-scale circulation anomalies, Clim. Dyn. 17, 5-6, 457-466.

Rex, D.F., 1950, Blocking action in the middle troposphere and its effect upon regional climate. Part I.: An aerological study of blocking action, Tellus 2, 196-211.

Scherrer S.C., M. Croci-Maspoli, C. Schwierz and C. Appenzeller, 2002 : Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the euro-atlantic region. Int. J. Climatol., 26, 233-249.

Shabbar A., J. Huang and K. Higuchi, 2001: The relationship between the wintertime North Atlantic Oscillation and blocking episodes in the North Atlantic. Int. J. Climatol., 21, 355–369.

Tibaldi, S., F. D'Andrea, E. Tosi, E. Roeckner, 1997, Climatology of Northern Hemisphere blocking in the ECHAM model, Clim Dyn 13, 649-666.

Trigo, R.M., I.F. Trigo, C.C. DaCamara and T.J. Osborn, 2004, Climate impact of the European winter blocking episodes from the NCEP/NCAR Reanalyses, Clim. Dyn. 23, 17-28.

Extratropical cyclones

From autumn through the winter and well into spring, extratropical storms dominate the weather across Europe. The development of several extratropical cyclones over the North Atlantic can have devastating effects on the European economy, especially when these storms move over the continent. The Anatol-Lothar-Martin sequence of December 1999 caused more than 150 lives to be lost and cost an estimated 18.5 billion Euros in economic damage. Most of the factors discussed below for PV steamers are relevant in the case of extratropical cyclones. In addition, the role of moisture and latent heat release seems to be crucial. The severe winter storms occurring over Europe all have an initial situation with a long and straight region of high baroclinicity stretching across the Atlantic towards Europe with a tongue of very high moisture content on its equatorial flank. Sensitivity area calculations often point to the mid to low troposphere (Hoskins and Coutinho, 2005). It is not clear why these levels are more important than upper levels. A further question relates to the inconsistency of deterministic and ensemble forecasts of extratropical cyclones in which sequential forecasts alternate between predictions of a strong or a weak system. The ensemble forecast tends to follow the deterministic forecast rather than providing both solutions within the ensemble. It is not clear whether it is associated with particular synoptic scale flow patterns or with nonlinearity in the flow evolution.

Hoskins B.J., and M.M. Coutinho, 2005: Moist singular vectors and the predictability of some high impact European cyclones. Q. J. Roy. Meteor. Soc., 131, 581—601.

Polar weather

Significant weather is not unusual in polar regions. The low troposphere and quite often small static stability cause rapid small scale developments (Polar Lows and Arctic fronts). There are strong contrasts in stability and temperature with ample possibilities for shallow low level baroclinic zones to develop. Standard baroclinic instability theory may be used to show that critical wavelengths for baroclinic growth may occur at wave lengths significantly shorter than for middle latitudes. In addition, release of latent heat by convection plays an important role developing these small scale systems. Unfortunately, these events are often poorly predicted in regions that are of significant importance to society. Verification results from the Norwegian Meteorological Institutes operational limited area numerical model system show that the model scores significantly better in the North Sea than in the Barents Sea (see Fig. 3). This may cause worries for future activities in the area. In addition to being one of the richest fishing areas of the Northern Atlantic, the Barents Sea will be an important area for gas and oil exploitation in the next decade.

Polar regions are data sparse in terms of conventional observations making numerical weather prediction a difficult task. In order to initialise NWP models properly, one therefore needs to rely on satellite observations. Unfortunately, satellite data assimilation presents unique challenges in polar regions. In particular, the orography over Greenland and Antarctica, the varying surface properties (e.g., old and new ice, open leads), stable atmospheres and low clouds all make the determination of the surface emissivity difficult which limits the use of satellite remote sensing. There is a need to focus on improved data assimilation for these regions.

Cloud physics at high latitudes is an area where climate as well as NWP models need to be improved. Low clouds are an important factor for the Arctic climate. At low latitudes low clouds have a cooling effect. At high latitudes, however, when low clouds appear over snow- or ice covered surfaces with high albedo, their effect can be different. In addition, special radiation properties alter their role as compared to low latitudes. Parameterisation of clouds is difficult in general. In the Arctic there are additional problems: The poor description/understanding of the boundary layer (Baklanov et al., 2008) causes wrong heat- and humidity fluxes and this have effects on the parameterisation of clouds. Low temperatures, low absolute humidity and stable conditions give conditions which current parameterisation schemes are not tuned for (Beesley et al, 2000). It is therefore a need for observations/measurements to improve and test parameterisation schemes.

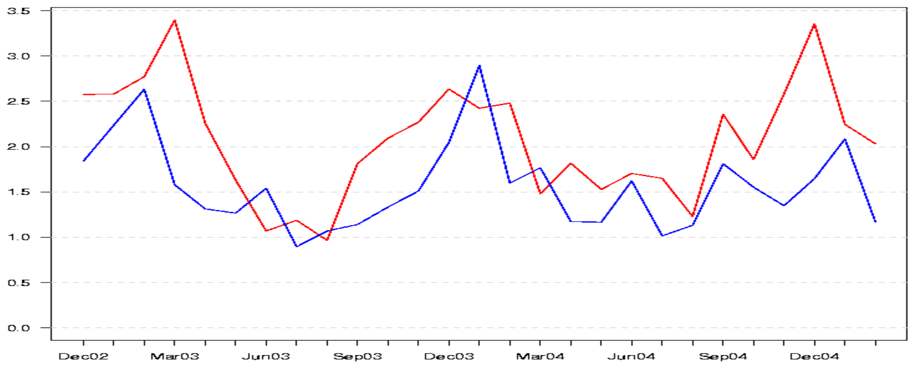


Figure 3 - Monthly mean RMS error of mslp from the Norwegian Meteorological Institute's operational numerical weather prediction model from December 2002 to February 2005 for Bear Island in the Barents Sea (red) and the oil platform Ekofisk in the North Sea (blue)

Mediterranean Cyclones

Mediterranean cyclones have climatologically smaller scales and shorter lifetimes than their Atlantic cousins, probably due the confined nature of the Mediterranean basin, surrounded by significant orography (Genoves et al., 2006). Several studies have focused on the characteristics of the cyclones in the Mediterranean area, on locations, frequency and temporal variability of cyclogenesis, and on their behaviour (Alpert et al., 1990; Trigo et al., 1999; Maheras et al., 2001; Lionello et al., 2002). These studies have shown that Mediterranean cyclones are often initiated by secondary cyclogenesis in which the orography plays a major role and have preferential regions of formation and subsequent prevailing paths (e.g. Gulf of Lions, Gulf of Genoa, Alboran Sea, Adriatic Sea, and Tyrrhenian Sea). Results obtained from the MEDEX project have recently shown that severe weather in the Mediterranean is mainly associated with cyclones, though not necessarily strong ones, especially for heavy precipitation (Jansà et al., 2001). An overview of cyclones in the Mediterranean and their impact in the environment can be appreciated in Lionello et al. (2006). Different physical ingredients have been found to be favourable to cyclogenesis (or cyclolysis): orography (usually cyclogenetic but not always), sea surface temperature, heat fluxes, latent heat release, degree of baroclinicity, subsynoptic structure and intensity of the upper-level precursor trough, etc (Trigo et al., 2002). However, the relative importance of synoptic versus local influences is poorly understood.

In the Mediterranean, small scale (tens of km) vortices resembling tropical cyclones or polar lows (Tropical Lake Cyclones or "Medicanes") are observed to develop over the sea with a frequency of the order of a few per year or less, mainly in autumn and winter. They are associated with strong winds (often exceeding 30 m/s) and convection, that can have an impact in the rather rare cases landfall occurs. Sometimes this type of shallow vortices appears in the core of larger scale cyclones or upper air lows (Emanuel, 2005; Fita et al, 2007). Mesoscale models seem to be able to forecast the genesis of "Medicanes" in the Mediterranean somehow better than expected, but only for short range (24-48 h) forecasts.

In addition, there is clear evidence that the interactions between Atlantic tropical cyclones and themid-latitude flow tend to decrease the predictability of Rossby wave packets propagating towards the Mediterranean. (see later discussion of downstream impact of ET).

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Deep Midlatitude Convection

Deep convection is present in most severe meteorological hazards (cyclones, storms, heavy rain, etc.) and is often the basic phenomenon leading to flash-flood generation. In spite of a large and continuous research effort, its parameterization as a sub-grid scale process is still the weakest point of numerical weather prediction models and fails to reproduce the overwhelming complexity of real-world moist convection. Year after year, models continue to exhibit lower levels of skill in predictions for the summer months (see Fig.4). Although cloud resolving models (CRM) are not foreseen at the global scale within the next 10 years, these models can now be run for long periods and over large domains or, alternatively, can be used in a global model as super-parameterisation (Grabowski, 2004). Both approaches clearly indicate potential improvements. However, the gain in predictability that they should provide has not yet been quantified. In particular, the question of refining ensemble forecast systems (by adding extra members or by designing mesoscale EPS) versus running a CRM high-resolution deterministic forecast has not been addressed so far. Convective precipitation forecasting raises some other challenging questions in terms of data assimilation and probabilistic forecasting as there are no established procedures either for assimilating cloud scale observations or for constructing a forecast ensemble for high-resolution domains. Although most of these questions are more relevant for short-term and limited area forecasting, the question of how uncertainties on microphysical processes will impact the uncertainties in predicted large-scale motions is relevant for all the THORPEX scales and remains completely open. Some of the issues relating to the interaction of intense convective storms and the synoptic flow are being investigated in the summer of 2007 in the COPS and ETreC 2007 field programmes (Wulfmeyer et al., 2007). Another under-observed and under-investigated factor is the boundary layer water vapour / moisture content and its distribution/structure. This is not only vital for the predictability of deep convection but has also been shown to have a strong influence on the strength of heavy precipitation events (Martius et al., 2006).

Predictability here is a major question – we still have not answered the fundamental question about synoptic versus topographic forcing, and their relative predictability. This kind of work follows from IHOP, CSIP, COPS, feeding into larger-scale NWP.

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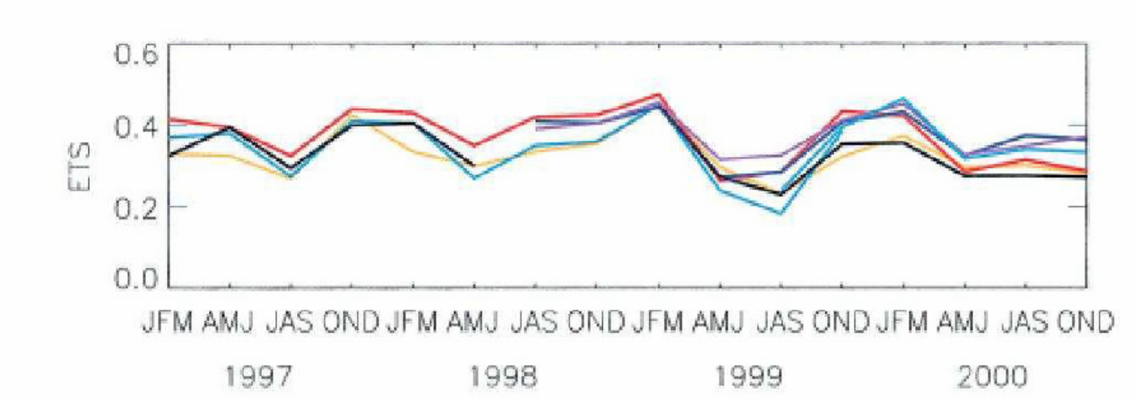

Figure 4 - Time evolution of equitable threat score for precipitation over Germany between Jan. 1997 and Dec. 2000 for a rain threshold of 2 mm/d. The forecast validity times are 42h (ECMWF, red line) and 30h (other models)

Orographic flow (tip jets, föhn, bora, mistral, mountain waves)

Mountainous orography affects atmospheric flow and its predictability in a wide variety of ways. On the one hand, upscale effects of orographic flow modification need to be properly accounted for in global medium-range forecast models in order to avoid systematic forecast errors. The most widely known example is the parameterization of wave drag and low-level blocking induced by unresolved topography, which has a history of almost 20 years but still requires substantial refinements. However, orographically triggered convection and the related latent heat release and gravity wave formation may also have significant upscale effects, but current convection parameterizations still have large deficiencies in predicting orographic convection. Inclusion of sub-grid scale orographic information and processes might be one way of making progress in this field (e.g., Rotach and Zardi, 2007). In addition, resolving/predicting boundary layer inversions accurately is often key in simulating orographic flow. Another major challenge is the assimilation of surface and low-level atmospheric data in mountainous regions, where currently most of the available information is discarded because the stations lie below the resolved model topography.

On the other hand, predicting the local weather impacts related to a given synoptic environment is particularly challenging in mountainous regions. Generally speaking, forecasters are confronted with a kind of a downscaling problem, linking the larger-scale, hopefully well predicted, fields to the expected local weather phenomena. For short-range forecasts (lead times up to 3 days), high-resolution limited-area models more and more allow for a direct simulation of local flow features, but it is important to keep in mind that steep orography imposes special requirements on numerical models in terms of numerical accuracy, adaptation of physics parameterizations and data assimilation. For longer time scales, statistic-dynamical downscaling of medium-range (probabilistic) forecasts might be a promising approach, particularly in the context of estimating the risk of high-impact weather.

Compared to flat regions, steep mountains increase the likelihood of high-impact weather events, particularly those related to heavy precipitation. Steep orography not only enhances precipitation intensities but also favours rapid runoff with the possible consequence of flash floods, and entails the risk of avalanches in winter. Thus, the special efforts needed to improve weather forecasts in mountainous regions are opposed by significant possible benefits for society and economy, which could be realized by enhancing the lead time for severe weather warnings. In this context, it needs to be pointed out that mountains do not necessarily decrease the predictability at small scales. For example, the steady orographic forcing tends to favour locations of preferred triggering of convection, and the spatial variability of stratiform precipitation is also to a large extent controlled by the orography. The important point is, however, to exploit this predictability for increased forecast skill.

Upper-level forcing: Potential vorticity (PV) streamers

Narrow quasi-meridionally aligned troughs are a frequent feature of atmospheric flow at tropopause levels. On a tropopause-transecting isentropic surface, they are identifiable as PV streamers extruding from the stratospheric reservoir of high potential vorticity (Fig. 5). Observations indicate they are prevalent at the downstream end of the mid-latitude storm tracks and develop as a consequence of Rossby wave breaking events. These upper tropospheric troughs are often accompanied by heavy precipitation events over Europe, which can be strongly amplified by orographic forcing (Massacand et al., 2001; Hoinka and Davies, 2007). According to the climatology, PV streamers associated with daily precipitation exceeding 30mm on the Alpine south side occur 3 or 4 times per year (Martius et al., 2006; Hoinka et al., 2006).

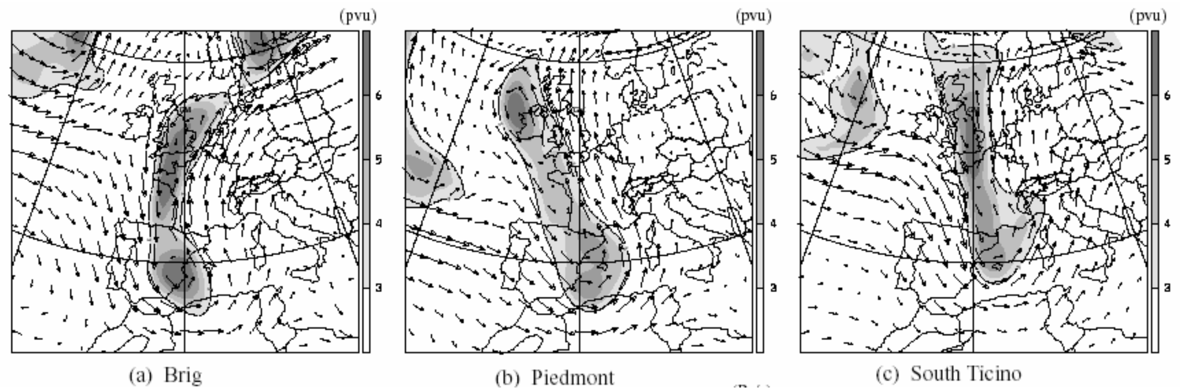

Figure 5 - Distribution of mean potential vorticity and air-flow at 200 hPa for three major rain events that affected a) the city of Brig (23 Sep. 1993, 300mm in 4h), b) the Piedmont (5 Nov. 1994, 250mm in 24h), and c) South Ticino (13 Sep. 1995, 327 mm in 36h). From Massacand et al., 1998

In order to quantify the role of PV streamers for predictability it is necessary to quantify when and under what conditions such events occur, and how well they are represented in NWP systems. Factors seen as important for the initiation and evolution of PV streamers include extratropical transition of tropical cyclones, vortices in the polar stratosphere, diabatic processes, orographic influences. Open questions with regards to forecasting PV streamers relate to whether a PV streamer will develop or not, how well a pre-existing PV streamer will be assimilated, whether the evolution is well forecast and the representation of the wave-mean flow interaction accurate? The relative importance of the mesoscale PV structure for the initiation of high impact weather compared to local processes such as soil moisture beneath it are not well known. In addition, the influence of the horizontal and vertical (particularly at tropopause level) model resolution and the physical parameterizations must be assessed.

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Upper-level forcing: Cut off low systems (COLs)

Cut off low pressure systems are closed circulations in the middle and upper troposphere developed from a deep trough in the westerlies. In isobaric maps (absolute topography maps), cut off lows are easily recognized as close geopotential contours with a cold core. This is due to the fact that the air within the low has its origin at a higher latitude. Its intensity is higher in the upper troposphere, decreasing downward and being even possible to find anticyclonic circulation at surface. As a general rule, the troposphere below cut off lows is unstable and convective severe events can occur, depending on surface conditions. Cut off lows are associated with many substantial forecasting problems, mainly due to the different characteristics of the terrain and to the presence/absence of a warm ocean that permits/ inhibits convection. Thus, the precipitation distribution associated with cut off lows is a challenge to predict, especially when the precipitation is due to convection over a warm sea. Cut off lows can bring moderate to heavy rainfall over large areas. In particular, they are among the most important weather systems that affect southern Europe and northern Africa and are responsible for some of the most catastrophic weather events in terms of precipitation rate (Nieto et al, 2007a). Furthermore, cut off lows are also important mechanisms of stratosphere–troposphere exchange (Holton et al., 1995). In a recent multidecadal climatology in the Northern Hemisphere Nieto et al (2005) confirmed and climatologically validated several characteristics of COLs: 1) the existence of three preferred areas of cut off low occurrence (Fig. 6). The first one extends through southern Europe and the eastern Atlantic coast, the second one is the eastern North Pacific, and the third one is the northern China–Siberian region extending to the northwestern Pacific coast; the European area is the most favoured region; 2) the known seasonal cycle, with cut off lows forming much more frequently in summer than in winter; 3) the short lifetime of cut off lows, most cut off lows lasted 2–3 days and very few lasted more than 5 days; and 4) the mobility of the system, with few cut off lows being stationary. Furthermore, the long study period made it possible to find a bimodal distribution in the geographical density of cut off lows for the European sector in all the seasons (with the exception of winter). An analysis in the European region (Nieto et al., 2007b) showed 1) that there is a very large interannual variability in the COLs occurrence at the annual and seasonal scales, although without significant trends. 2) that the influence of larger scale phenomena is seasonally dependent, with the positive phase of the NAO favouring autumn COL development, while winter COL occurrence is mostly related to blocking events. During summer, the season when more COLs occur, no significant influences were found. The influence of stratospheric circulation on the European occurrence of COLs has been also studied. So, Gimeno et al (2007) performed an exploratory analysis on the effect of the timing of the stratospheric vortex breakup in the occurrence of COLs in the Northern Hemisphere. The analysis showed that, at latitudes lower than 45ºN, COLs are more frequent for earlier vortex years during the following spring and summer, being this result especially important in the European sector.

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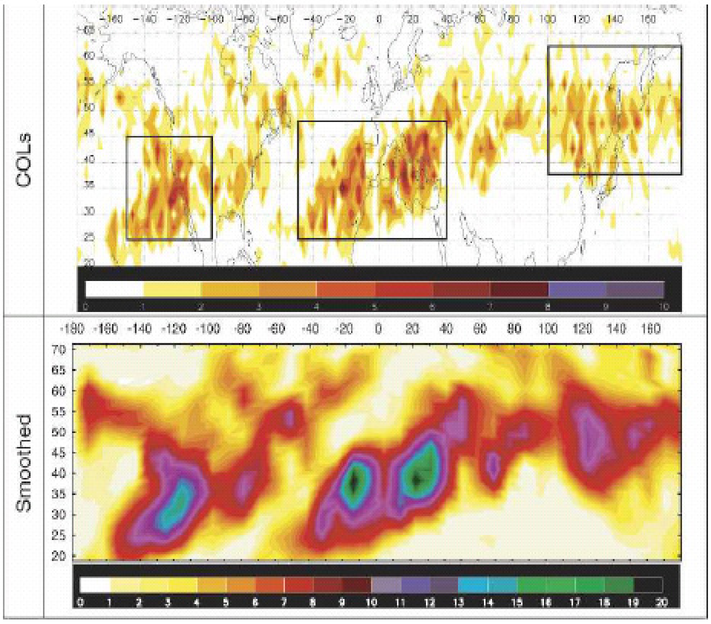

Figure 6 - Total number of cut off lows by grid points (2.5ºx2.5º) for the period 1958-1998 (top). A smoothed version calculated for boxes of 5ªlatx10º lon (bottom)

Tropical influences: Downstream impact of the Extratropical Transition of tropical cyclones

A significant number of tropical cyclones move into the mid latitudes and become extratropical cyclones (Jones et al., 2003). This process is referred to as extratropical transition (ET). The climatology of Hart and Evans (2001) shows that ET in the North Atlantic occurs in 45% of the cases with a peak frequency in the early and late hurricane season (i.e. September and October). During ET, a cyclone frequently produces intense rainfall, strong winds and large waves, posing a serious threat to land and maritime activities. Although these extreme conditions severely impact the region of the ET, there are also significant impacts downstream of the ET event. Often, the movement of the tropical cyclone into the midlatitudes imposes significant perturbations to the midlatitude flow that may rapidly extend downstream and to a lesser degree upstream of the location of the extratropical transition event. The large amount of variability in the downstream response to an extratropical transition suggests that there are important sensitivities to a variety of physical mechanisms associated with the forcing on the midlatitude flow. These mechanisms may include basic baroclinic energy conversions, forcing of diabatically-forced Rossby wave-like circulations, and enhancements to downstream jet streaks. All of these factors would exhibit sensitivity to a variety of interactions with a decaying tropical cyclone. Finally, use of ensemble prediction systems indicate that the downstream forcing due to an extratropical transition is typically associated with reduced predictability as defined by variability among members of an ensemble prediction system (Harr et al., 2008; Anwender et al., 2008).

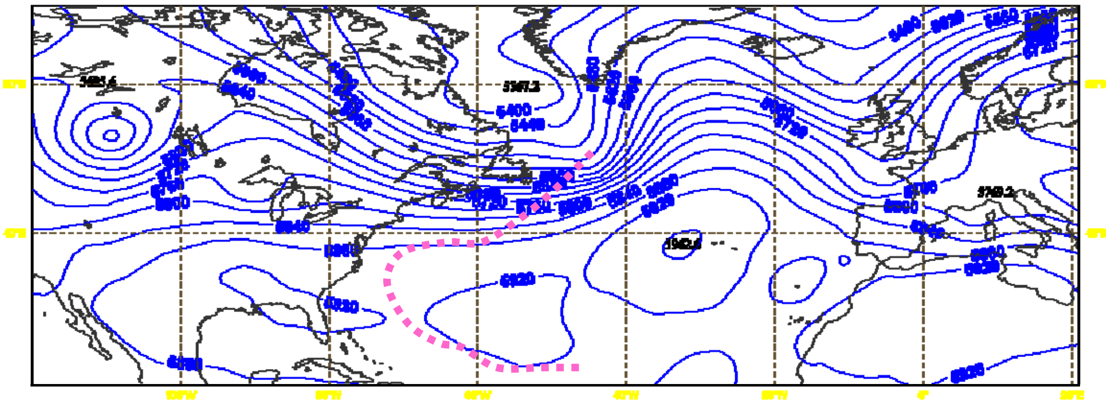

Figure 7 - Track of the tropical cyclone IRENE 10 days before its interaction with an upper-level trough, superimposed on the 500hPa geopotential chart of 19 Aug. 2006, 00 UTC. Any ensemble forecast initialized prior to the meeting time exhibits a remarkable spread over the Mediterranean (as illustrated in Figure 8)

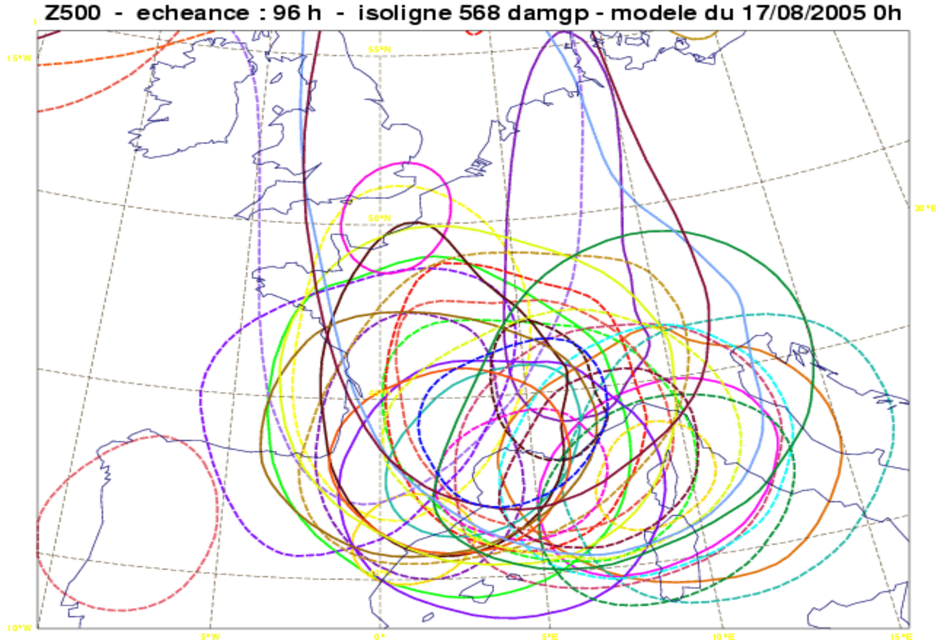

Figure 8 - ECMWF ensemble forecast initialized 96h prior to the interaction of Irene with the upper-level trough (5680m contour of the 500 hPa geopotential)

The impact of an ET on the midlatitude flow has been shown to be directly linked to reduced predictability for high-impact weather events far downstream of the original ET event (Figs. 7 and 8). Therefore, there is a strong requirement to assess the extent of the sensitivity to various physical mechanisms during ET. These mechanisms include the impact of sensible and latent heat fluxes, precipitation distribution, frontogenesis, and baroclinic energy conversions. Finally, the character of the downstream response to ET should be placed in the framework of the mean environmental conditions (i.e., baroclinic wave guides) across the entire ocean basin in which the ET is occurring.

Although recent research has identified important physical processes that define the ET process, there has been little progress on characterizing the influence of specific mechanisms on the variability and predictability of downstream impacts. Although there is promise for increased observations that may be obtained from in situ or remote platforms, there is a great deal of uncertainty as to what impact new or additional observations will have on forecasts sequences of the ET and related downstream flow. Therefore, key issues regarding mechanisms, observations, and impacts remain to be addressed to increase understanding of the role(s) of ET on impacts of predictability over a variety of time and space scales.

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Tropical influences: Organised tropical convection

It is generally recognised that organised tropical convection impacts the predictability of weather systems in the Euro-Atlantic sector. The realistic representation of tropical convection in global atmospheric models presents a significant challenge for numerical weather prediction. Key uncertainties are associated with the MJO and convectively coupled waves, intra-seasonal variability of monsoons, easterly waves and tropical cyclones, tropical-extra-tropical interaction, and the diurnal cycle. Our knowledge of key physical processes determining organised tropical convection is incomplete, in particular with respect to the interactions on scales from individual clouds to planetary flow patterns, to the links to microphysical processes, and interaction of tropical convection with the midlatitude flow and its variability. It is essential to make progress in improving the representation of tropical convection in large scale models. For example, the extent to which representations of complex physical processes such as the dynamics of convective updrafts/downdrafts, the interaction between convective and stratiform clouds/rain, mesoscale organization, the development of cold pools, and the coupling among dynamics, microphysical and radiative processes impact the midlatitude predictability is not known. Research into the impact of tropical convection on European predictability should take place within the YOTC framework.

Tropical influences: West African Monsoon

Coupling between the West African monsoon and the mid-latitude circulation occurs through a variety of processes. African Easterly Waves and associated convective perturbations can propagate from Sahel to the tropical Atlantic Ocean where the presence of a subtropical trough can sometimes recurve the trajectory of moist tropical air toward the mid latitudes. In favourable conditions (especially during late summer - early autumn), this can amplify baroclinic processes near Morocco and the Spanish peninsula. During the peak of the West African monsoon, in July and August, the Heat Low over the Sahara has a very variable position from Algeria to Libya, Mauritania to Chad. The induced atmospheric circulation can have some influence on the Mediterranean region and southern Europe. The activity of the West African Monsoon modulates the intensity of the subtropical westerly jet, and the descending branches of the associated Hadley and Walker circulations. The associated anticyclonic surface circulation has some impact on the mid-latitude circulation. All these questions must be tackled in close coordination with the THORPEX African regional plan.

Polar influences

In addition to forecasting challenges within the polar regions there are challenges with regard to polar influences on middle latitude weather. One example is the impact of polar processes on middle latitude populated regions as Greenland with its high topography has a significant effect on a number of weather phenomena at high latitudes in Europe. The combination of Greenland's high topography and the data sparse area of Northern Canada make the area important as an initiation place for surprise developments hitting Europe with a relatively short lead time. Klinker and Ferranti (2000) investigated the poor performance of the ECMWF model for the summer of 1998 as compared to the 1999 summer, and showed that analysis errors in the polar area can have a detrimental impact on forecast skill over Europe. The result is likely to be dependent on the flow conditions. For the period they considered, a strong baroclinic flow extended from Greenland over the North Atlantic into Europe. The flow in the vicinity of Greenland is also important for climate studies as the strong winds impact the ocean dynamics and may affect the climate and other aspects of the Earth System through affecting the thermohaline circulation.

A significant number of extratropical cyclones move into polar latitudes and “give birth to” polar lows. This process – the Arctic Transition of Extratropical cyclones - may be regarded as the polar parallel to Extratropical Transition. As extratropical cyclones end their life cycle in Northern Scandinavia a reversed shear northerly flow develops in their western flank creating favourable conditions for polar low developments (Grønås et al., 1987; Nordeng, 1999). The climatology of Kolstad (2006) shows that these conditions are set up as frequent as 15% of the time during winter storms in the Northern Atlantic As the small scale cyclones moves southwards and eventually make landfall in Scandinavia, Britain or Denmark they frequently produce intense snowfall, strong winds and large waves, posing a serious threat to land and maritime activities. Accurate prediction of storm track and timing of the events have shown to be a major forecasting task in numerical weather prediction.

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Heat lows

A thermal low is a warm, shallow, non-frontal depression which forms above continental regions, mostly in the subtropics, but also in the lower mid-latitudes. It occurs during the summer months because of the intense surface heating over land. The main areas of occurrence are regions with arid or semi-arid surfaces where there is little surface evaporation. The basic physical process responsible for generating a thermal low is the vertical expansion of the lowermost layers of the atmosphere due to convective heating, which produces divergence above these layers. The divergence aloft results in a lowering of the surface pressure. Thermal lows are more frequent in spring and summer and their genesis and lysis are modulated by the daily cycle of temperature. Their occurrence is therefore depending on the amplitude of this cycle and on the land sea temperature difference. Many of them remain shallow depressions confined to the lower troposphere, Modelling studies suggest that they are also generated over sea, but in autumn and winter, when the land-sea temperature difference is reversed (Lionello et al., 2006).

The thermal low occurring above the Iberian Peninsula is the most prominent example of its type in Europe, but less intense thermal troughs have been observed also at higher latitudes in Europe. Typically, shallow convection forms in the low, but precipitation is not generated in this dry environment. Strong surface pressure gradients occur at the periphery of the low and these cause low-level winds to blow from the coastal zones towards the interior of the peninsula (Hoinka and Castro, 2003). Although the Iberian Peninsula is surrounded by sea, there is no significant moisture transport towards the semi-arid peninsula's centre where most thermal lows are located.

Some of the key questions related to forecast are:

- What determines the strength of the heat low?
- How far are land - and sea-breezes influenced by the thermal low?
- Under which circumstances interacts the Iberian thermal low with the Saharian one?
- Which role plays the synoptic-scale environment on the thermal low's evolution?
- Which large-scale conditions favour the generation of a thermal low?

Also, the export of low—stability air from Spain over northwestern Europe (the so-called 'Spanish plume') can lead to severe weather over a number of days.

Hoinka, K.P. and M. Castro, 2003: The Iberian Peninsula thermal low. Q. J. R. Meteorol. Soc., 129, 1491 - 1511. (Corrigendum 2006, Q. J. R. Meteorol. Soc., 132, 1377)

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Air quality

It is becoming increasingly clear that short-lived pollutants (such as aerosols and ozone) from one region can be rapidly and efficiently transported to other regions (e.g. from North America to Europe, from Europe to Asia and North Africa), making local emissions an international concern. The main transport pathways at short- and medium-range can be easily captured with tagged tracers. However, this is not yet common practice in the meteorological centres. For example, long-range transport episodes of dust from Africa to Europe are frequently and easily observed but are still poorly documented and predicted, whereas they may have a significant impact, including on the dynamics of the jet. Besides their impact on air quality, aerosols strongly affect radiation, cloud microphysics and possibly convection initiation. They should therefore be better represented in numerical weather prediction models.

LIST OF THORPEX SERIES PUBLICATIONS

1. International Core Steering Committee for THORPEX, Third Session, 16-17 December 2003, Montreal, Canada. Final Report. WMO/TD-No. 1217, WWRP/THORPEX No. 1.

2. M.A. SHAPIRO, A.J. THORPE, 2004: THORPEX International Science Plan Version 3. WMO/TD-No.1246, WWRP/THORPEX No. 2.

3. International Core Steering Committee for THORPEX. Fourth Session 2-3 December 2004, Montreal, Canada. Final Report. WMO/TD-No. 1257, WWRP/THORPEX No. 3.

4. THORPEX International Research Implementation Plan Version 1. WMO/TD-No. 1258, WWRP/THORPEX No. 4.

5. First Workshop on the THORPEX Interactive Grand Global Ensemble (TIGGE), Reading, United Kingdom, 1-3 March 2005, WMO/TD-No. 1273, WWRP/THORPEX No.5.

6. Symposium Proceedings - The First THORPEX International Science Symposium, 6-10 December 2004, Montreal, Canada, WMO/TD-No. 1237 WWRP/THORPEX No. 6.

7. Symposium Proceedings – The Second THORPEX International Science Symposium, 4-8 December 2006, Landshut, Bavaria, Germany, WMO/TD-No. 1355, WWRP/THORPEX No. 7.

8. International Core Steering Committee for THORPEX. Sixth Session 25-27 April 2007, Geneva, Switzerland. Final Report. WMO/TD-No. 1389, WWRP/THORPEX No. 8.

9. The YOTC Science Plan – A Joint WCRP-WWRP/THORPEX International Initiative. WMO/TD-No. 1452, WCRP-130, WWRP/THORPEX No. 9.

10. African Science Plan – Version 1. WMO/TD-No. 1460, WWRP/THORPEX No. 10.

11. WWRP/THORPEX African Implementation Plan – Version 1. WMO/TD-No. 1462, WWRP/THORPEX No. 11.

12. International Core Steering Committee for THORPEX. Seventh Session 18-20 November 2008, Geneva, Switzerland. Final Report. WMO/TD-No. 1495, WWRP/THORPEX No. 12.

13. International Core Steering Committee for THORPEX. Eighth Session 2-4 November 2009, Offenbach, Germany. Final Report. WMO/TD-No. 1522, WWRP/THORPEX No. 13.

14. Weather Research in Europe – A THORPEX European Plan. – Version 3.1. WMO/TD-No. 1531, WWRP7/THROPEX No. 14.