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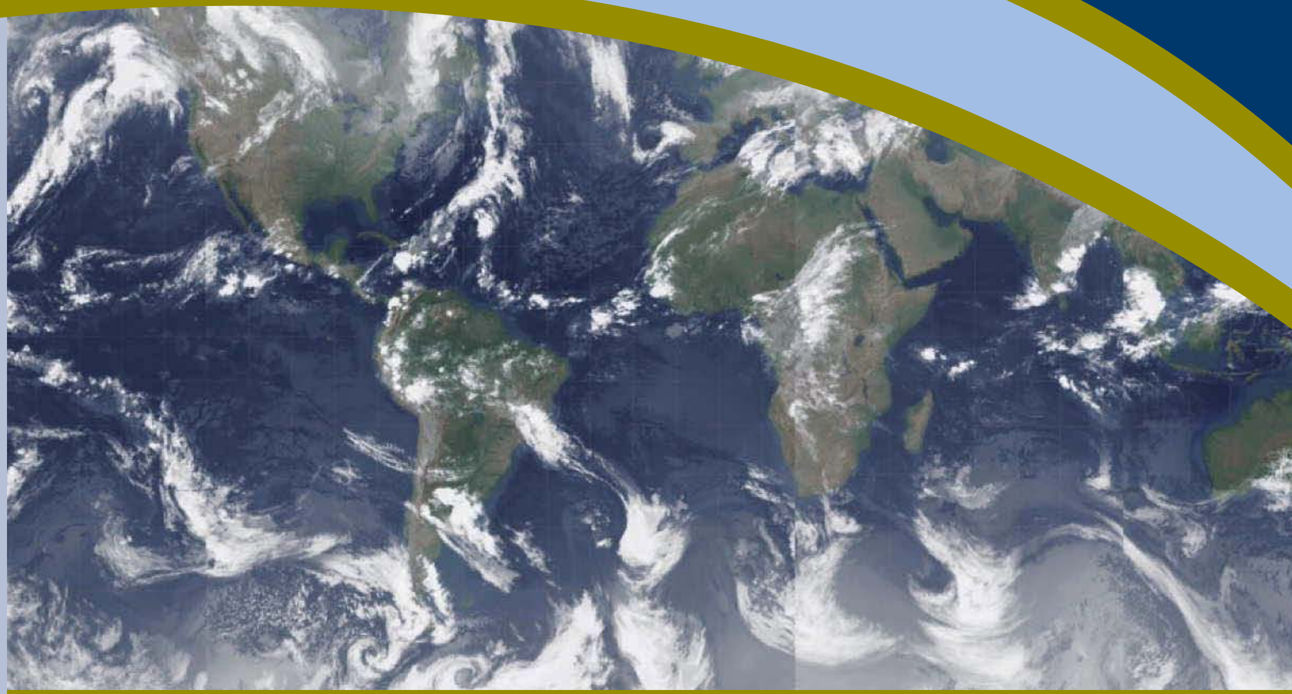
THORPEX INTERACTIVE GRAND GLOBAL ENSEMBLE

LIMITED AREA MODEL PLAN



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THORPEX INTERACTIVE GRAND GLOBAL ENSEMBLE LIMITED AREA MODEL PLAN (TIGGE LAM)

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Foreword

The TIGGE-LAM panel was set up by the GIFS-TIGGE working group to coordinate the contribution from Limited Area Model (LAM) Ensemble Prediction Systems (EPS) to TIGGE (the THORPEX Interactive Grand Global Ensemble, *Bougeault et al. 2010*) and to the proposed GIFS (Global Interactive Forecast System). After a couple of years of activity, the Panel was requested by the WWRP Joint Scientific Committee to develop a Strategic Plan outlining the main scientific and development issues on which TIGGE LAM must concentrate to advance LAM EPS and defining specific activities related to these issues. Furthermore, the sensible increase in resolution, both in deterministic and ensemble model applications, is making more and more evident the importance of establishing a broader long-term effort within the WWRP that focuses on improving skill of Mesoscale short-term regional forecasts. This means that discussions need to take place between the different groups with interests in this subject.

The over-arching goal of TIGGE-LAM is to replicate many of the TIGGE successes, while complementing and augmenting TIGGE by enabling weather-prediction advances at the mesoscale and within a LAM framework. TIGGE has led to many peer-reviewed publications advancing weather prediction science, while forming the foundation for long-term cooperative efforts amongst global operation numerical weather prediction (NWP) centres. The fundamental nature of LAM prevents every centre from contributing to global studies, but enough instances of overlapping spatial domains exist to warrant pursuit. Additionally, we can expect that LAM will be a basic component of weather-prediction suites even while global-model grid spacing approaches 10-km for deterministic forecasts, and tens of km for global ensembles. LAM and LAM-EPS will necessarily go further down in scale, and the basic challenges associated with boundary conditions and fine-scale modelling will persist. TIGGE-LAM will enable generalizations of TIGGE results across scales, while addressing the potential benefits of localized fine-scale modelling.

Background to LAM EPS development is discussed in Section 1 where also TIGGE LAM is introduced. The relationship with the GIFS-TIGGE WG and with North America Efforts are explained in Section 2 and 3 respectively. Section 4 and 5 will describe the main scientific issues related to LAM EPS and Section 6 will present the specific actions to be undertaken.

1. LIMITED AREA ENSEMBLE PREDICTION AND TIGGE-LAM

High impact weather (HIW) events, when the weather is also severe, often have a mesoscale or convective-scale component (e.g. mesoscale convective complexes producing heavy rainfall and flash floods, polar lows, or orographic precipitation enhancement) and such events have a large impact on society, the economy and the environment.

Deterministic Limited Area Modelling (LAM) has allowed explicit, and skilful, prediction of scales that cannot feasibly be predicted with global models. During the last decade, high resolution, non-hydrostatic models have been shown to better capture severe weather events (e.g., RDP D-PHASE results, *Rotach et al. 2009, Bauer et al. 2011*) even when the deterministic approach is still subject to large uncertainty in space and time. Because predictability time scales are shorter at smaller scales, uncertainty is unavoidable. The successful operational application of global ensemble prediction systems (EPS) at forecasting centres worldwide has thus been extended to LAM to produce probabilistic forecasts complementing deterministic products.

Considering that Global EPS systems are moving to higher resolutions (ECMWF EPS moved to T639 ~30 km at the end of January 2010), the main added value from LAM EPS in the future will be in the representation of phenomena at convection-allowing scales [O (1 km)]. As growing computational power allows LAM to be deployed at finer resolutions, open scientific and technical challenges will remain. Some challenges are specific to particular phenomenon or scales, while others are endemic to LAM in general. In the latter case, scientific discovery addressing general problems with current-generation LAM will benefit future systems at cloud-permitting scales and below.

The TIGGE-LAM plan is being developed with the philosophy that scientific and technical development of LAM-EPS will benefit future systems as well:

- Knowledge gained about mesoscale predictability and ensemble construction provide a basis for future global mesoscale EPS
- The ability to deal with LAM for ensemble prediction provides a basis for convection-allowing (and finer scale) probabilistic prediction with ensembles

The community of EPS researchers and developers should avoid a conservative vision based on the present modelling systems. Models and EPS systems are evolving. Many open problems remain for mesoscale EPS, and new questions will emerge as prediction scales become finer. LAM will be a viable tool to complement global EPS for the foreseeable future. As global EPS improves and is implemented to predict finer scales, LAM will remain valuable for dynamic downscaling applications. Dynamic downscaling with numerical weather prediction models in combination with mesoscale data assimilation is still the most powerful methodology for predicting small-scale high-impact weather with fidelity. Statistical downscaling, although a powerful framework for a certain class of users, is at present not applicable to represent complex dynamic structures such as deep convection. Extreme events, which are climatologically unlikely, are also difficult to predict with statistical techniques.

According to the THORPEX core objectives, GIFS-TIGGE is focussed on the optimization of the use of ensemble forecasting to maximize the forecast skill (*Bougeault et al. 2010*). TIGGE LAM is intended to coordinate actions to evaluate which are the events whose predictability can be improved by the use of LAM EPS. TIGGE LAM should stimulate and support activities to define how best to implement ensemble prediction systems to address regional and local HIW events.

Any progress on global ensemble production and archiving to support TIGGE LAM will facilitate research on the application of dynamic downscaling of forecasts from a variety of global ensemble prediction systems and with the introduction of other perturbations associated to local processes. Following current plans, the GIFS concept should be shaped and implemented over a few years, but the GIFS design must remain valid for a much longer period. HIW will certainly remain with us, and TIGGE-LAM should contribute to the definition of strategies and methodologies to improve HIW and severe weather predictive skill, including uncertainty prediction.

TIGGE LAM activity will be developed by:

- Facilitating communication and exchange of information
- Providing guidelines
- Fostering research
- Coordinating activities

With the following main objectives:

a. To contribute to the definition of scientific issues to advance LAM EPS
b. To reinforce the link and cooperation with the other WWRP working groups with crossing competences
c. To support and foster research on LAM EPS:
    - By promoting actions to make the access to LAM EPS products easier
    - By coordinating / stimulating / participating in specific initiatives to address the relevant scientific issues (e.g. Research & Development Projects or Forecast Demonstration Projects, RDPs/FDPs)
d. To coordinate the archiving of limited-area ensemble forecasts by providing standards and guidelines and as a complement to the TIGGE archive
e. To facilitate the interoperability of the different LAM-EPS
f. To facilitate the implementation of new LAM EPS

The experience gained during the first period of activity made it is clear that TIGGE LAM cannot coordinate all the aspects of the cooperation in place for global systems (TIGGE). Guidelines, standards, directives, scientific priorities, sharing of tools and methodologies should be valid globally, but specific initiatives and applications must be organized at regional levels between the THORPEX Regional Committees, regional forecast centres and the national hydro-meteorological services.

2. RELATIONSHIP BETWEEN THE GIFS-TIGGE WG AND TIGGE-LAM

The GIFS-TIGGE working group has two main objectives:

- First, to enhance international cooperation in ensemble prediction, between both operational NWP centres and the academic community. The TIGGE project facilitates research on ensemble prediction methods, especially methods to combine ensembles, correct systematic errors, and aid in decision-making. This is achieved by coordinating the archiving of operational global ensemble forecasts from ten NWP centres, and making them available to the research community via three TIGGE data centres.

- Second, to coordinate research and development leading to a future Global Interactive Forecast System (GIFS). The objective of GIFS is the production of improved probabilistic forecasts of high-impact weather, using research and development based on the TIGGE data set and other aspects of the THORPEX research programme. GIFS entails the development of prototype forecast products, initially focused on predictions of tropical cyclones. Subsequent GIFS products will be aimed at improving forecasts of precipitation, and then other high-impact weather.

The TIGGE-LAM panel was set up by the GIFS-TIGGE working group to coordinate work on regional ensembles, and complement the focus of GIFS-TIGGE on global ensemble forecasts. The GIFS-TIGGE working group agreed to a set of standards for archiving the global ensemble forecasts, and agreed to a standard set of forecast fields to be archived using GRIB2 format. The TIGGE LAM panel has adapted these standards for the archiving of LAM EPS products, as detailed in section 6.3. It has also been agreed that high-priority TIGGE-LAM parameters will be archived at one of the three TIGGE data centres, on a regional basis.

It is envisaged that regional ensembles from TIGGE LAM will contribute to the development of the GIFS, by optimizing the use of the products of the existing systems and via the participation to relevant RDPs and FDPs. A GIFS development project will focus on the development of products to improve the prediction of tropical cyclones and high-impact precipitation for particular regions (initially Southern Africa and the SW Pacific), in conjunction with the WMO Severe Weather Forecast Demonstration Project. A North-West Pacific Tropical Cyclone Forecast Project will focus on improving the forecasts of tropical cyclones in that region. Products based on LAM EPS systems, where available, will supplement products available from the global TIGGE data, and demonstrate the additional benefit obtainable from higher resolution ensembles.

There is a close working relationship between GIFS-TIGGE and TIGGE LAM. Some of the members of the GIFS-TIGGE working group are also involved in the TIGGE LAM panel, and the chair of the TIGGE LAM panel is a member of the GIFS-TIGGE working group.

3. RELATIONSHIP TO NORTH-AMERICAN EFFORTS

The TIGGE-LAM is positioned to enable interaction amongst North-American nations, and also interaction with European efforts. It also serves a complimentary role to past, current, and future efforts within the U.S., including:

- The American Meteorological Society (AMS) ad-hoc Committee on Uncertainty Forecasting (ACUF) elaborated the need to produce and communicate forecast uncertainty in their report, key enterprise Gap #2. This TIGGE-LAM plan is proposing a more detailed research and development agenda for progress on regional ensembles.
- The Developmental Testbest Center (DTC) Ensemble Testbed (DET) is pushing development on a regional ensemble system meant to simulate many aspects of NCEP's Short-Range Ensemble Forecast (SREF) system, enabling more rapid transition of

research to operations. The TIGGE-LAM plan may help guide research needed before testing in an operational environment can begin. The research itself can also be enabled by the cooperation under TIGGE-LAM.

- The North American Unified Operational Capability (NUOPC) programme is a collaboration between the operational forecasting components of NOAA, the U.S. Navy, and the U.S. Air Force. It seeks to provide robust operational capability for a wide range of users, and leverage the benefits each organization can provide from their oft-different foci. Cooperation between LAM-EPS groups now will help motivate and guide a LAM component of NUOPC. Simultaneously, code standardization efforts under NUOPC may aid in design and implementation of a North America TIGGE-LAM archive.

4. BASIC SCIENTIFIC CHALLENGES

A primary goal of ensemble prediction is to represent and quantify the uncertainty in numerical weather prediction. Alternately stated, ensembles should predict a verifying probability density function (PDF) as estimated from observations. This uncertainty results from the many approximations and errors inherent to an NWP system, both during the assimilation of meteorological observations and during the model integration, which manifest in linear and nonlinear growth of errors during a forecast. Sources of uncertainty are often conceptually separated into those arising from initial conditions and those arising from model inadequacy. Because methods to identify and attribute the error sources are limited, and the challenge is considerable, ensemble LAM research and development have proceeded largely through trial and error. Often, attempts are made to account for both model and initial-condition uncertainty. Theory guides approaches to handle initial-condition uncertainty. Empirical results, and the argument that mesoscale HIW is strongly tied to (perhaps poorly) parameterized processes in models, indicate that consideration of model uncertainty is important to mesoscale EPS. Because of the lack of sufficient theory to account for model inadequacy, an EPS is tested for quality a posteriori with probabilistic verification.

Ensemble prediction represents an honest forecasting approach given inevitable uncertainty, and a logical way to account for these limits by complementing deterministic products with probabilistic information. Higher resolution than global models means LAM EPSs may better represent and account for uncertainty affecting local and regional processes. We assume that large-scale uncertainty is determined by lateral boundary conditions, although further work on this topic may be appropriate.

Representation of multiscale forecast uncertainty can be complicated when perturbations are separately introduced in a global EPS and a LAM EPS. Upscale error growth on a LAM domain is limited by the domain size, and downscale error forcing from large scales are limited by temporal and spatial truncation in the lateral boundary conditions derived from a global EPS. The interaction between the large-scale perturbations and those in the LAM domain are not well understood. Many possibilities to generate and couple these perturbations are tractable and theoretical guidance is lacking. Development and testing of LAM EPS prototypes may be necessary to support the requisite empirical research. Much of this work has been completed, and as a community we are poised to leverage this work toward greater gains in understanding and improving probabilistic forecast skill.

Although the TIGGE LAM panel is not committed to fund or execute scientific inquiry, it is important to set out the main scientific issues and challenges related to LAM EPS. TIGGE LAM will contribute to research by facilitating the availability of LAM EPS products to the research community and by promoting coordinated research initiatives in cooperation with the GIFS-TIGGE and the other WWRP working groups. TIGGE LAM should also create a natural environment to stimulate the cooperation between the LAM EPS community and the other groups with closely related activities. A real advancement in mesoscale forecast skill must be achieved by a strong coordination and cooperation with the WWRP Mesoscale Research working Group and with the WGNE group. Research activities must be defined to allow the numerical experimentation necessary to test and improve LAM, and address HIW events with impacts that vary regionally. As it is ongoing for TIGGE and the GIFS, it is essential to have a close link with the Verification WG and with SERA to assess the quality and the added value coming from LAM EPS and to define how probabilistic information can optimally be exploited on regional and local scales. The economic value of forecast and application models (hydrology, air pollution) must be included in the quality and impact assessment.

Primary challenges associated with mesoscale predictability and model inadequacy follow. As LAM-EPS is an attempt to account for those challenges, the specific challenges to LAM EPS design and implementation are discussed thereafter in Section 5.

4.1 Mesoscale predictability

Mechanisms for nonlinear and chaotic error growth, and the associated loss of predictability, are not well understood at mesoscales. Unlike large-scale baroclinic flows clearly displaying an up-scale error energy transfer, multiscale interactions involving the mesoscale are still the subject of vigorous debate. Also, the classic view put forth by *Lorenz (1969),* that smaller scales always lose predictability faster than larger scales (commensurate with faster eddy turnover times), does not necessarily hold under varying definitions of predictability. Up-scale error energy transfer may be limited; mesoscale forcing including, for example, land-surface fluxes and topography, can plausibly slow or limit error growth at those scales. The implication is that study of predictability addressing specific phenomenon may be required to asses and identify the main sources of limited atmospheric predictability on small spatial/temporal scales (several tens of km or smaller), and how their relative importance change with spatial and temporal scale. Lack of a unifying theory also means that finding optimal methods for simulating mesoscale error growth may be an empirical endeavour and best studied with ensembles, and we are only now approaching a maturity with mesoscale models that permits robust conclusions about mesoscale predictability.

Although fundamental knowledge is sparse, empirical evidence suggests that for many phenomena, for example garden-variety deep convection over flat terrain, can sometimes fit the Lorenz paradigm. Adopting a probabilistic approach to prediction is therefore imperative. Successes in global, large-scale, ensemble efforts motivate research and development at finer scales. Cooperation amongst several ongoing LAM efforts could provide the necessary experience and data to address the fundamental predictability problems. Classic measures of predictability, such as the Lyapunov exponent that reveals the typical rate of phase-space trajectory divergence in response to initial perturbations, are difficult to quantify analytically for complex NWP models, but large data sets enable statistical methods of quantification. Inasmuch as mesoscale predictability may be phenomenon-dependent, large samples of specific-event predictions are needed.

4.2 Mesoscale model inadequacy

Model errors combine with error growth from initial-condition errors to limit extrinsic (complete NWP system) predictability, and in practice reduce predictive skill. Despite the success of the NWP enterprise, objective methods for identifying and characterizing model inadequacy are not well-defined. Even if models improve and start to resolve key processes at the convection permitting scale, as orographically-induced convergence zones triggering convection (*Wulfmeyer et al. 2011b*), mesoscale processes are strongly forced by parameterized processes and total error at mesoscales may have proportionally more model error than at large scales. Model inadequacy is thus a serious barrier to improving predictions at these small scales.

We do not know how best to simulate error growth due to model inadequacy. The canonical use of multiple models has proven empirically valuable, but is likely not the best long-term solution and could possibly be slowing our efforts to find the best model. This problem does not disappear with the eventuality of global mesoscale ensembles because it is a fundamental challenge for mesoscale modelling.

A cooperative TIGGE-LAM effort could bring much to bear on the model error problem. Techniques to simulate model errors, such as stochastic perturbations to physics tendencies (e.g. *Buizza 1999, Reynolds et al. 2008, Berner et al. 2009, Bowler et al 2008*), are promising and more scientifically grounded. Balances and energetics used to formulate those perturbations are better-understood at large scales. Production of multi-model ensembles (and ensembles of ensembles) could prove valuable for defining the structures needed for effective mesoscale stochastic perturbations. Much research is needed, and the data sets produced by TIGGE-LAM again enables study with large samples.

5. ADDRESSING THE SCIENTIFIC CHALLENGES: LAM-EPS AND TIGGE-LAM

Cooperation and collaboration under a TIGGE-LAM framework can promote the need, and enable the research, to address the scientific challenges. Because many of the challenges lack guiding theory for addressing them, empirical efforts may prove most valuable; certainly empirical approaches are responsible for most LAM-EPS successes thus far. Empiricism will drive the understanding, and it is by nature a problem best addressed through cooperation amongst multiple modelling groups. Here we point out more specific challenges to optimizing LAM-EPS, providing a basis for cooperation. The TIGGE-LAM effort has a role in addressing each challenge.

5.1 Scale interactions for LAM embedded in global models

Intuitively, very high resolution short-range forecasting (1-3 km up to 24 hours) is expected to benefit from perturbations quite different from the perturbations increasing the skill of ensemble forecasting at 10-20 km resolution, continental scale at 72 hours forecast range. But much is still unknown. Interactions between continental and regional scale perturbations, and how to account for them in an EPS, are discussed by *Bowler and Mylne (2009)* among others: is it possible to generate local perturbations that improve LAM EPS skill when compared to a pure global EPS downscaling?

Scale interactions (or lack thereof) between LAMs and global EPS could be generally addressed by comparing uncertainty representation in different LAMs responding to the same global EPS. Results would elucidate the fundamental limitations of LAM EPS, and have direct bearing on the design of future LAM EPS.

5.2 Perturbations on LAM initial-conditions

Because of the general sweeping effect of the lateral boundary conditions for LAM (*Warner et al. 1997*), it is reasonable to assume that LAM EPS initial-condition perturbations will survive for a limited period of time. The effect is to first order a function of the mean flow velocity and the domain size, and somewhat independent from a perturbation technique that incites growing modes. Bigger integration domains will allow local perturbations to grow and transfer uncertainty upscale more, reaching greater total amplitude in the LAM domain. The effect of truncation in lateral boundary conditions from an EPS should also not be underestimated (Nutter et al. 2004). Time intervals between LBCs saved from global model integrations, and the relatively coarse resolution of global EPS, work to create an artificially large scale gap between the global model and a LAM. Consequently, the full uncertainty spectrum forecast by a global EPS cannot be imposed on the LAM.

It is again reasonable to hypothesize that dynamical consistency between local and boundary perturbations is favourable, but methodologies to assure this consistency require exploration. *Torn et al. (2006), Bowler and Mylne (2009), Bellus 2008, Bellus et al. (2011)*, investigate this problem, but broader conclusions may be possible.

The optimal way to determine efficient perturbations to the initial conditions is still matter of research in many groups, both for global and LAM applications (*Bowler 2006, Argence et al 2008, Bellus 2008, Bellus et al 2011, Wang and Bishop 2003, Wang et al. 2004, Wei et al. 2008*). The measurement for success remains demonstrable skill improvement compared to direct dynamical downscaling of a global EPS (*Montani et al. 2011*); many approaches appear to meet this demand, but with global models continuing to improve LAM-EPS requires continual improvement.

Active research on mesoscale ensemble-filters explicitly for prediction (as opposed to solely data assimilation) and ensemble-transform techniques for LAM-EPS is ongoing world-wide. Recent papers by *Bowler et al (2009), Hacker et al (2011b)*, shows that some technical challenges have been overcome but that the value of these techniques for mesoscale initial condition perturbations has yet to be realized (*Saito et al. 2011*).

Following what done for global EPS, dynamic conditioning approaches, such as singular Vectors (*Horányi et al 2011*), targeting of Global Singular Vectors (*Frogner and Iversen 2011*), breeding of growing modes (*Chen et al, 2010; Toth and Kalnay 1997*) are also under investigation for LAM-EPS. Some works describing a comprehensive evaluation and intercomparison of some of these techniques to generate local perturbations on initial conditions have been recently published (*Hacker et al 2011b, Saito et al 2011*); significant improvement over the direct dynamical downscaling is a common result. Mesoscale perturbations seem to bring improvement in the short-range, especially for intense precipitation, suggesting that continuing research in this direction is important.

5.3 Representation of model errors

Model errors combine with chaotic error growth from initial-condition errors to limit extrinsic (complete NWP system) predictability and in practice reduce predictive skill. The representation of model uncertainty, due to the structural deficiencies of numerical models, has been reviewed and thoroughly discussed during a recent workshop at ECMWF (ECMWF 2011).

Despite the success of the NWP enterprise, objective methods for identifying and characterizing model inadequacy are not well defined. If we believe that compared to large-scale error, total error at mesoscale has proportionally more model error, model inadequacy is a serious barrier to improving predictions. As yet we do not know how best to simulate error growth due to model inadequacy.

The dearth of theory for designing schemes to represent model uncertainty has not hindered a broad range of efforts that have empirically demonstrated improvements in skill. Multi-model and multi-physics techniques began over a decade ago (*Stensrud et al. 2000*) and have continued to this day. *Buizza et al. (1999)* proposed simple stochastic perturbations to a global model, and similar methods have recently been considered for application in regional models (*Torrisi 2011, Charron et al. 2010*). Others have perturbed parameters of the physics schemes (*Bowler et al. 2008, Gebhardt et al. 2011, Hacker et al. 2011a,b, Marsigli et al. 2010. Montani et al. 2011*). More complex schemes to replace energy lost by dissipation and other processes have been tested in global models (*Shutts 2005, Berner et al. 2009*), and have more recently been investigated in regional LAMs (*Berner et al. 2011*). *Reynolds et al. (2008)* perturbed variables directly in a global model by imposing a stochastic process that is a function of the tendency, and a similar approach has recently been introduced in NCEP's SREF. Intrinsic stochastic parametrization schemes are also under development (*Plant and Craig 2008*).

The canonical use of a multiple model or multi-physics ensemble (AEMET SREPS - *García-Moya et al 2011*, COSMO SREPS - *Marsigli et al. 2010*, NAEFS-LAM - *Du et al. 2010*, GLAMEPS-*Iversen et al. 2011*) to account for model errors by using different models has proven empirically valuable, but may not prove to be the best long-term path to improved LAM-EPS. The recent growth in other model-uncertainty schemes could be interpreted as evidence that efforts are finding greater success. Indeed the recently operational REPS at CMC does not use multiple models or schemes but is based on the scheme by *Charron et al. (2010*). CMC thereby avoids practical difficulties including maintaining multiple models or physical schemes, and disparity between physical variables in different schemes.

It seems possible that multiple models or physical schemes, because of their past success, may be valuable in understanding model uncertainty. Research toward this has been virtually non-existent, but a TIGGE-LAM archive effort could enable it. Access to ensembles using different perturbation schemes to the model equations or parameters may also lead to greater understanding of how those perturbation affect model dynamics, thereby accelerating research on stochastic perturbations. As pointed out by *Berner et al. (2011*), the simultaneous use of different strategies to represent multiple forms of model errors improves the quality of ensemble forecasts. In many cases the underlying reason for these results remains elusive. The mere fact that model perturbation schemes appear competitive or superior to multi-physics schemes indicates that continuing investigation could lead to further advances. In some cases this may require support from model development groups, which can advise and facilitate modifications to model equations or physical closure and forcing schemes.

It could be effective to account also for the uncertainty arising from the dynamical core of the model. Even if the differences between dynamical cores by themselves are smaller compared to differences related to physics, nonlinear interactions between dynamics and physics can elicit greater sensitivity when dynamics and physics differences are combined. This possibility has not been investigated yet.

5.4 Perturbations associated with soil/surface description

Detailed information to assign and evolve lower boundary conditions is increasing with more complex land-surface models, land-surface data assimilation, and space-borne sensors. Under dynamically unstable conditions at mesoscales (often statically unstable), small-scale and small-amplitude uncertainty in land-surface details can rapidly produce uncertainty in atmospheric states (*Berner et al. 2011*). As resolution increases, and modelled land surface-atmosphere coupling improves, we can expect sensitivity to fine-scale details of lower boundary conditions to become more important, and thus lower-boundary perturbations to represent uncertainty may grow in importance. Work on this subject has been sparse, but has gained some recent attention (*Horányi et al 2011, Wang et al 2010, Sutton et al 2004, 2006*).

Soil moisture is one of the most difficult soil-state variables to estimate and initialize in a model. It is well known that, especially if large scale forcing is weak, the impact of the soil moisture on local meteorological parameters can be extremely relevant when the atmosphere is dynamically unstable (e.g. *Cassardo et al 2002, Hauck et al. 2011*), but its importance diminishes under flow dominated by active large-scale dynamics.

Due to sparse observations, and to the strong dependency on local soil properties, in practice the soil moisture state leading to the most skilful near-surface forecasts is often used (*Mahfouf 1991, Hess at all 2008*). Improvements can be expected by assimilating data of new sensors such as cosmic ray soil moisture detection (*Zreda et al. 2008*), streamflow (*Warrach and Wulfmeyer 2010*), in-situ soil moisture networks, passive remote sensing (*Wigneron et al. 2003, Reichle et al. 2007*), and GPS (*Larson et al. 2008*).

Some recent work is continuing to build on our understanding of the role of soil moisture and temperature. For example, tests of soil-moisture and land-surface temperature initial condition perturbations are being done in the MOGREPS regional system (*Tennant and Beare 2011*). Instead of resetting the soil-moisture of all ensemble members to the same value as the control, the soil moisture in each ensemble member is cycled to corresponding ensemble members in the next forecast cycle. This results in a build-up of spread of soil-moisture in the ensemble, which helps to address the under-dispersive near-surface spread in the forecasts. The regional MOGREPS system derives its initial perturbations by rescaling the driving global model perturbations. New work is being done to modulate these land-surface temperature perturbations by a factor related to the orographic roughness, which aims to address errors of representativeness and station height mismatch in the surface temperature field. These extra perturbations show benefit in improved spread and reduced error of the ensemble mean during the first day of the regional forecast. The MOGREPS global system includes SST perturbations with a prescribed spatial-scale, which are also passed down to the regional model through the perturbed initial state.

Generally speaking all the parameters used to describe land-surface type and properties, including vegetation, could be included as sources of errors to be accounted for through suitable perturbations. Despite local perturbations in the initial conditions, these soil/surface perturbations are active throughout the model integration and can potentially be leveraged for near-surface forecasts. As yet we do not have good estimates of spatial scales or amplitudes of lower-boundary uncertainty. We also do not know how important that uncertainty is compared to other sources of mesoscale uncertainty.

5.5 LAM EPS and Data Assimilation

Ensemble-based data assimilation (EnsDA) is one area currently drawing much attention (*Meng and Zhang, 2007 and 2011, Tippet et al. 2003, Hamill 2006*). This is mainly due to the possibility to enrich the classical climatological background error statistics with time varying and flow dependent information. Arguably the most attractive applications are at mesoscale and smaller, where nonlinearities and the lack on known dynamical balances are severely limiting the application of the widely used variational approaches. To date, the benchmark in mesoscale DA is still set by 3DVAR and 4DVAR (*Seity et al. 2011, Dixon et al. 2009, Kawabata et al. 2011*). EnKF systems have to demonstrate that they are superior by detailed, well-designed data assimilation test beds. The development of these test beds is strongly promoted by WWRP MWFR

Ensemble-filter data assimilation is an emerging research topic, and those systems have not been thoroughly evaluated at forecast times beyond a few hours, but recent progress has been rapid and implementation efforts are underway for LAM-EPS (*Schraff et al 2011, Bonavita et al. 2010*).

Ensemble filters can be split into separate processes to update the mean (data assimilation) and update the perturbations. The Ensemble Transform Kalman Filter (ETKF) has been studied as an approach to generate ensembles centred on an analysis produced by a separate (usually variational) scheme, both for global (*Wang and Bishop 2003*) and regional (*Bowler 2006, Hacker et al., 2011b*) models, but to the best of our knowledge is currently not used for any regional LAM-EPS.

Comparisons of probabilistic skill resulting from perturbation cycling using filtering techniques, and the more self-consistent approach offered by ensemble filters, are sparse. The simpler method of perturbed observations in individually cycling data assimilation systems is another candidate receiving only sparse attention. *Burgers et al. (1998)* showed the equivalence with other ensemble data assimilation systems under conditions of large ensembles, linear systems, and Gaussian errors. Limitations and benefits of these approaches for LAM-EPS are still unclear given inevitable sampling error and model inadequacy.

Many of the ongoing activities on this subject can be found on the web site of the Joint SRNWP Workshop on DA and EPS, held in Bologna at ARPA-SIMC on 23-25 February 2011 (EnsDA 2011). As pointed out in this workshop, there is general agreement EPS and DA can be complementary goals and share many components, but it is not always clear what will be the most fruitful path of research and development. Several aspects still need to be investigated and many questions are still quite open to make EPS suitable for DA. How strong is the requirement for a single-model ensemble for DA? Can multi-physics be useful, even if it produces non-Gaussian distributions that may be detrimental to DA methods? How is sampling error from small ensembles affected by use of multiple models or physics schemes? In a hybrid ensemble-variational DA system, how can we optimize the use of all information in the ensemble and eliminate unwanted noise? Is it possible to formulate a weak-constraint EnKF, similar to weak constraint 4D-Var?

A few studies suggest to potential benefits for employing multiple models and multi-physics (*Meng, and Zhang, 2007*) in an ensemble data assimilation system. But the overall approach is a fundamental violation of the assumption that each ensemble member is a sample from the same statistical distribution. In practice this would be violated by clustering of ensemble members according to model, resulting in a multi-model distribution in the distribution of prior states. Ensembles of ensembles, available via a TIGGE-LAM cooperation, could be studied with this in mind. For addressing these questions, a strong collaboration and coordination of research activities is very beneficial for instance by data assimilation research test beds. TIGGE-LAM may be designed in order to reach same of the data assimilation research test bed requirements which have been formulated by WWRP MWFR.

5.6 Verification methods and research required to assess the added value/societal benefit of regional LAM EPS systems

Verification has always been one of the basic components of Numerical Weather Prediction. It is fundamental to assess the quality of the forecasting systems and, by identifying model deficiencies, to drive further development. As pointed out by *Casati et al (2008),* verification must satisfy various needs: input to modellers by identifying weaknesses, to forecasters as a guidance to support products interpretation and to the many different specific users to optimize the use of meteorological forecasts. Proper verification requires a large number of forecasts to establish statistical significance and be sure of results. Global forecast systems can take advantage of global observations spanning many weather and climate regimes simultaneously, and can be rigorously evaluated with relatively few forecast periods. Regional models are not afforded this, and instead many forecast periods are needed. Rare events add to the difficulty. TIGGE-LAM may enable sound verification efforts if an archive is established.

Verification is characterized by a broad spectrum of difficulties and interesting challenges. The quality of a forecast, both deterministic and probabilistic, is composed of several different aspects (*Murphy 1993b*) and it is not straightforward to gain a complete measure of the quality of a forecast. Some of the parameters most affecting society, such as precipitation, are best described by non-normal time and space distributions that are difficult to handle. Mesoscale phenomena such as deep convection produce distinct “features” in predictions that are not easily described by parametric statistics. For the same reason that forecast skill may be absent by quadratic metrics when, in a very high-resolution forecast, a feature is predicted realistically but at a slightly different time or location than observed, ensemble members may have little to no overlap in small-scale features. Metrics such as RMS spread are then not helpful.

During the last decade, a lot of cooperative work has been done also thanks to the coordination from the Joint Working Group on Verification (JWGV) under the World Meteorological

Organization (WMO)/World Weather Research Programme (WWRP) and the WMO Working Group on Numerical Experimentation (WGNE). The verification community has responded with feature-based verification, such as MODE (*Davis et al 2009*), and methods to quantify uncertainty suggested by an ensemble may have to change similarly.

Even if much progress has been made, it is necessary to continue international cooperation on verification. Several verification questions related to LAM EPS still require research, including:

- Which is the best combination of probabilistic verification techniques?
- Which are the best methodologies to have a fair intercomparison between Global EPS and km-scale ensembles?
- How to evaluate the added value coming from resolution?

Perhaps the greatest challenge for regional EPS systems is to accurately assess the probability of (often rare) extreme events (*Murphy 1991a*), which may be far more important in terms of societal impact than “normal” weather.

- How best to do this for LAM EPS systems?
- Is an alternative approach to, e.g., ensemble bias correction required in order to best support the accurate forecasting of extreme events, as opposed to the forecasting of normal weather?
- Assess how probabilistic verification of LAM EPS systems compares to probabilistic verification of the deterministic model with statistical post-processing. Does LAM EPS offer added value over the latter?

5.7 Biases and calibration

Members of ensemble systems need to be highly credible in themselves if they are to adequately represent the probability density of atmospheric parameters. How can the ensemble best be treated if this basic assumption is not met? Are there ways to deal with model error (bias in particular) within LAM EPS systems?

Currently, highly reliable and sharp probabilistic forecasts with mesoscale information results only after a calibration technique has been applied (cf. *Raftery et al 2005*). In the absence of a nearly perfect mesoscale model, the need for calibration will persist. Because the expense of producing large data sets appropriate for calibration is substantial, most calibration research has been completed with global models from operational centres with longer archives, and in many cases simplified versions of global models.

Mesoscale variability introduces further challenges to statistical methods. For example, mesoscale error statistics may be less Gaussian and may not be well defined by any known parametric distribution, requiring large ensembles to characterize the distribution. In this sense precipitation is again a problem due to its statistical properties. Even if different techniques have been developed and implemented (*Hamill and Whitaker, 2006*), and sophisticated QPF distributions employed (*Sloughter et al 2007*), calibration of high-resolution precipitation in complex terrain is still a challenge (*Diomede et al. 2010, Flowerdew 2011*).

Classical statistics, and most notably statistics assuming normal distributions, are effective at describing typical behaviour, but many are ineffective at characterizing extreme events. In a calibration context, the result is a temporal smoothing (or filtering) of the raw forecasts, and extreme events will be predicted less often. Research is needed to find the methods for mesoscale calibration that can handle extreme events, which are endemic to smaller scales and local weather. Results may inform future decisions about ensemble sizes and model resolution to produce highly reliable and sharp forecasts under calibration.

Research in this direction will also contribute to quantify the tradeoffs between ensemble size, model diversity, and resolution when a good calibration method is available and to compare the benefits of multi-model ensembles with the calibration of a single model using the reforecast data. Initial data for limited area model reforecasts needs to come from a reanalysis carried out with an up-to-date NWP system, so this topic is closely related to regional reanalysis efforts.

Following the way opened by TIGGE (*Hagedorn et al. 2010*), a large and diverse mesoscale ensemble data archive will lower the technical barrier for researchers to propose and test calibration approaches.

5.8 Convection-allowing EPS

The expected benefit coming from higher resolution is stimulating the community to develop and test LAM-EPS at the cloud permitting (allowing) scale. Convection-allowing ensembles will stress even the most mature verification and calibration systems. Convection-allowing implementations are still at the range of scales where assumptions underlying many physical parameterizations break down (dubbed “grey zone” or “no-man’s land”), and almost nothing is known about how to form stochastic perturbations for those scales. The collaborative environment promoted by TIGGE-LAM may help facilitate study of these issues even while research and implementation continues.

A lot of research and regular testing is ongoing at the Centre for Analysis and Prediction of Storms in Oklahoma, where a high-resolution multi-model LAM EPS system is used (*Clark et al 2011*). The system comprises three models, the WRF-ARW model (*Skamarock et al. 2008*), the WRF-NMM model (*Janjic 2003*) and the ARPS model (*Xue et al. 2001*). Among the results, this work shows that the incremental gains in skill decrease with increasing the number of members and that more members are required as forecast lead time increases and spatial scale decreases. These results appear to indicate the broadening of the true forecast PDF of future atmospheric states associated with decreasing spatial scale (faster error growth at smaller scales) and increasing forecast lead time (growth of analysis/model errors).

NCEP developed HREF, a 4 km LAM EPS, for operational implementation, This system is created by combining the 32-km 21-member SREF with 4-km high-resolution window NMM and ARW runs to produce separate 44-member ensembles over the eastern U.S., western U.S. and Alaska.

In Europe, km-scale ensemble activity is quite intense and many initiatives are already addressing operational implementations. The German weather service, DWD, developed a convection-permitting ensemble named COSMO-DE EPS (*Gebhardt et al., 2008; Gebhardt et al.*

2011). In the pre-operational suite they are running 20 members, and 40 are planned in the operational implementation, of COSMO-DE at 2.8 km resolution nested in 7 km resolution COSMO run driven by BCs extracted from different operational Global Models run at their highest resolution (deterministic suites). Model errors are accounted by running different configuration of COSMO-DE. The model runs are to be performed 8 times per day with 21 hours lead-time. The start of the operational phase is scheduled during 2012. Further developments will include a switch to the ICON model as the driving EPS, and the use of an EnKF for initial condition perturbations.

In early 2012, the Met Office is planning to introduce a 12-member convective-scale system (MOGREPS-UK) to detect high-impact localised weather events. This ensemble grid spacing is approximately 2.2 km over the UK. MOGREPS-UK is embedded within the regional MOGREPS-R and runs 4 times a day. To begin with the only perturbations will come from the coarser-resolution driving ensemble. In cooperation with Reading University, the Met Office has been developing a research-oriented convective-scale EPS that produces its own IC perturbations (*Migliorini et. al. 2011, Bannister et al. 2011*).

MeteoFrance is developing an 8-member 2.5-km ensemble based on AROME (*Vie et al, 2011*). The AROME ensemble is currently in a research stage and it is planned to be operational by 2015. The major focus in the development of this system is on Initial conditions perturbations. A strong participation to HyMeX is planned with an experimental prototype of AROME EPS.

Cooperation on these CP LAM EPS is particularly important in Europe where, at the present time, many LAM EPS systems are already running with substantial overlapping of the integration domains. Coordinated actions could give answers to some basic issues connected to the importance of resolution compared to the ensemble size at lower resolution. This last point is also extremely relevant to support strategic planning about computer resources.

TIGGE LAM should also try to support coordinated actions to provide suitable set of boundary conditions to facilitate research on convection-permitting and, in the near future, convection-resolving LAM EPS systems.

5.9 Probabilistic forecasts for other modelling applications

Models of other processes that use NWP output as input include both technical (diagnostic and dynamic) models, and models of decision processes (often called decision aids). Probabilistic mesoscale predictions pose new challenges to those applications because the error structures and variability are different from either deterministic forecasts or large-scale ensembles. If we assume that better ensemble predictions can theoretically lead to better predictions from other models or automated decision support, then research and development is needed to take advantage of mesoscale ensembles.

Data sets such as those that may be generated from a TIGGE-LAM project could help decision-aid developers learn to make use of mesoscale probabilistic forecasts. Many decision aids cannot directly ingest probabilistic information, and simply running many realizations may not be an option because of limited computational capability in rapid decision scenarios. Use of output from multiple models when dynamical variables have different inherent scales of variability, and physical variables may not even have the same meaning among models, is a practical complication.

TIGGE-LAM could also be important for overcoming challenges associated with diagnostic and dynamical models used in secondary predictions. The practical problem of the meaning of variables within a model code also exists here. More fundamentally, if a secondary model does not follow statistical linearity, for example resulting in a linear transformation of a PDF or more trivially predicting a Gaussian pdf from Gaussian input, further challenges arise. Questions regarding whether to run an ensemble of the secondary models or to use the model to map NWP PDFs to PDF in other variables need to be studied.

To have a comprehensive picture of the value of LAM EPS to end users, it is important to assess the benefit of the non-atmospheric uncertainty information by coupling LAM EPS and other modelling applications. The limits of predictability need not only to be tested for the atmospheric variables but also for subsequent processes, e.g. discharge simulations in hydrology. *Thielen et al. (2009)* have made a first assessment on multi-scale predictability for floods, but concluded that longer time series of multi-ensembles are needed, in particular when assessing extreme events.

Coupling of probabilistic meteorological forecasting with discharge prediction was one of the first applications leading to important international initiatives. Among these:

HEPEX (http://www.hepex.org/) is the Hydrologic Ensemble Prediction Experiment bringing together hydrological and meteorological communities from around the globe to build a research project focused on advancing probabilistic hydrologic forecast techniques

EFAS (http://efas-is.jrc.ec.europa.eu), the European Flood Alert System, that is being developed at the Joint Research Centre in close collaboration with the National Centres in the member states.

In the Po river basin an advanced application of coupled meteorological-hydrological-hydraulic ensemble prediction system has been developed (*Casicci et al. 2011*). This system is driven by the different precipitation scenarios from the 7-km COSMO LEPS (*Montani et al. 2011*), plus one more precipitation forecast from the deterministic run of COSMO over Italy, and three different hydrological/hydraulic modelling chains for a total of 54 discharge predictions every 3 hours. This system allows to evaluate different aspects of meteo-hydrological predictability and to quantify the relative importance of the different modelling components.

Besides hydrology, applications based on LAM EPS are increasing quite rapidly: storm surge forecasting (*Flowerdew et al. 2010*), sea wave forecasting (*Carrasco and Saetta 2008*), air quality (*Delle Monache et. al 2008, 2006*), and fog forecasting (*Zhou and Du 2010*).

6. ACTIONS AND ACTIVITIES

Current operational weather forecasting is based on a wide range of numerical modelling systems. Deterministic models with their associated assimilation schemes, probabilistic systems based on ensemble suites, separate large-scale (synoptic) through mesoscale and down to the emerging cloud-resolving suites, are often individual components of an NWP programme. The different part of the forecasting systems are changing and evolving together, and it is necessary to be adaptive and to keep a very high level of coordination among all the groups which are interconnected by having common scientific interests.

As already pointed out, TIGGE LAM coordination cannot be solely at the global level because of the intrinsic regionalism of LAM-EPS. The management and coordination cascade must be defined region by region, and activities must be planned taking the best possible advantages from already existing initiatives.

WWRP, THORPEX and GIFS-TIGGE represent a unique opportunity to coordinate LAM-EPS activity both at scientific and implementation level. WWRP offers the opportunity to have cross-coordination with the closely related working groups. THORPEX provides the organizational basis to LAM-EPS to contribute to the improvement of Weather Forecasting with specific reference to regional HIW. GIFS TIGGE represents the main reference since TIGGE LAM must complement global EPS by adding value where and when higher resolution and local optimization can play a substantial role.

Actions should then cover all the initiatives necessary to exploit at best the unique potential coming from being part of these Programmes.

6.1 Action 1: Maintain an appropriate structure and composition of the TIGGE-LAM Panel

After the first period of activity, the Panel has been reorganized with a regional structure (Annex 1) to facilitate the progress of TIGGE-LAM. The Panel composition and structure has to be constantly adapted in order:

- To give more emphasis to the Regional component of TIGGE LAM and to facilitate the focus on regional activities.
- To have Panel members who are in the position to give direct contributions to the activities.
- To involve representatives of other working groups with common interests

Regionalization is extremely important when the forecasting of High Impact Weather is the aim. The Impact of a natural event most of the times depends on its intensity but the vulnerability of the territory and of the population must be also taken into account to quantify the Impact of such event in terms of damages, loss of properties and casualties. The integration of all these information can be done only with a strong involvement of local bodies and authorities.

6.2 Action 2: Definition of the key issues in regional ensemble forecasting

The definition of Key issues in LAM EPS is a continuously evolving process including both scientific and practical aspects. Scientific issues must be defined with a specific focus on the different Regional HIW events and with a close link with the scientific activities of the Regional THORPEX Committees and described in the Regional THORPEX Plans. The new regional structure of the TIGGE LAM Panel should help in this sense.

6.3 Action 3: Set up of TIGGE-LAM Databases to contribute to the TIGGE archive

The TIGGE archive is a major achievement of the worldwide TIGGE cooperation as a contribution to the research on EPS and Predictability. Since the very beginning of TIGGE-LAM, the inclusion of LAM EPS products to the TIGGE archive has been discussed and planned. With respect to the global TIGGE, due to the regional implementation of LAM EPS systems (not overlapping in most of the regions), it is more difficult to appreciate the usefulness of these archives especially when devoted resources to implement these archives are not available.

Apart from the practical implementation, some coordination has been set-up and some standards defined. These guidelines should be taken as a reference to support the organization of the regional archives. Following what done by TIGGE, a list of TIGGE LAM output parameters was defined and are reported in the ANNEX 2 to this plan. A sub-set of parameters, labelled as High Priority (HP) have been selected and these HP parameters should be archived at the three TIGGE Archiving Centres, NCAR, ECMWF and CMA, following a geographical/Regional competence principle (i.e., data from European systems at ECMWF, data from the Americas at NCAR, Asian data at CMA). As regards the data access, the same policy adopted by TIGGE will be proposed. TIGGE GRIB2 coding has been also defined as a standard.

In the first period, to make the access to these products as easy as possible, it was proposed to archive TIGGE LAM products on a standard geographical lat/lon grid at 0,1° resolution.

Due to the recent increase of resolution of LAM EPS, archiving at the original resolution on native grids is now suggested.

Ongoing related activities

Asia: CMA regional LAM EPS is now archived at CMA.

Europe: HP parameter archiving activities at ECMWF are planned to start at the end of 2011 thanks to resources available in the framework of the GEOWOW project. The SW required to retrieve and manage the LAM EPS products will be also developed. GEOWOW (GEOSS interoperability for Weather, Ocean and Water) is an EU-funded FP7 project started in September 2011.

North America: feasibility is currently ongoing.

6.4 Action 4: Definition and adoption of the TIGGE LAM data policy

TIGGE LAM data providers should agree about data access policy following what has already been formulated by the TIGGE data providers. The proposal for delayed data access is the same as for TIGGE; a delay of 24 hours instead of 48 hours will be proposed.

The data policy referred to the real-time availability of TIGGE LAM products for GIFS related activities will be evaluated and determined at the proper time.

Real time availability of products during FDPs and RDPs will be asked specifically from time to time.

6.5 Action 5: Implementation of regional observational/analyses dataset for objective verification of mesoscale deterministic and ensemble forecasting

Observational datasets suitable for model verification are usually available for limited periods of time, and over restricted areas, in correspondence to scientific projects, RDPs or FDPs.

It would be necessary to coordinate activities to implement regional observational dataset in regions where observational networks are particularly dense or rich in information which can be used to asses modelling systems skill in forecasting high impact weather events. In regions where national policies put severe restrictions on the availability of data from local networks, alternative solutions should be identified to allow scientific investigations while preserving the commercial value of the data. TIGGE-LAM participants can be advocates for the production of further high-resolution analyses. The availability of suitable analysis or observational data, and the adoption of common methodologies for verification, could accelerate research to achieve decisive results based on high quality data and tools.

Ongoing related activities

Europe: some contacts are established with ECMWF and other initiatives based on ongoing projects (EU-EURO4M) and Programmes (EUROGRID). This issue is also recognized as a priority by SRNWP.

North America: Combined gauge and radar precipitation are produced operationally at NCEP.

6.6 Action 6: Interoperability Aspects - Define standards to exchange meteorological fields required as initial and boundary conditions

The interoperability concept covers many aspects related to the ease of use of operational products exchanged among different centres. At the basic level, interoperability means standardisation of field format, coding, transmission, etc. At the higher level, it includes the possibility of coupling different GLOBAL and LAM systems. This task is really tough both as regards the development of the required SW interfaces and also the long-term sustainability. It implies a high level of communication and coordinated SW maintenance by the involved centres.

TIGGE LAM approach is to sustain initiatives in this direction, to cooperate, where and when possible, on the different technical and scientific aspects and to facilitate the exchange of information. Actions and agreements must be taken through specific initiatives. The definition of guidelines and standards will make cooperation easier and faster during RDPs, FDPs or other project campaigns.

Ongoing related activities

Europe: link is established with the SRNWP Interoperability programme, a three-year EUMETNET programme started in September 2008 and lead by the Met Office with the participation of the four European consortia.

The deliverable of this Programme are:

- Deliverable D1: A report documenting the definition of a standard output format (hereafter ‘standard format’), including a list of parameters for which the standard format will be applied. An initial plan for maintenance of this standard will be provided.
- Deliverable D2: Documentation describing the requirements and specification for the adaptor software (software tools for conversion between different data formats and model grids; hereafter referred to as ‘adaptors’).
- Deliverable D3: Four adaptors that transform the output from every LAM to the standard format and vice versa. Documentation will also be provided. Each consortium is responsible for provision of the software.

- Deliverable D4: Deliver enhancements to existing adaptors to enable LAMs to process data from the four global model providers. This includes documentation. In addition, deliver enhancements to existing adaptors to allow LAMs to process data from any other LAM. This work is the responsibility of each consortium.
  The Programme is fully successful with just some delay due to GRIB2 coding extra work.
  At the time of writing, the extension of this Programme is under planning.

6.7 Action 7: Development and provision of LAM EPS products in the GIFS perspectives

The development of the GIFS concept comprises the development of ensemble based products tailored to optimize the forecasting of weather parameters associated to HIW. Tropical Cyclone tracks and intensity is the first of a list including precipitation and wind gusts in the second and third position respectively.

The original vision of a strongly interactive component of the GIFS, including on-demand LAM EPS runs, is now strongly scaled down. This approach could be evaluated on specific site but it cannot be adopted as a general reference and the contribution from TIGGE LAM must rely mainly on systems which are already in place and running.

With this constraint in mind, it is clear that the patchwork coverage of LAM EPS makes the inclusion of TIGGE LAM in the GIFS products development more awkward.

Experience gained during projects, at different levels and especially during FDPs and RDPs, and during regional co operations will be extremely helpful to this aim.

6.8 Action 8: Set-up of cross-working group discussion between TIGGE-LAM and the other WMO working groups with cross-cutting interests

Ensemble prediction relies on numerical models able to reproduce the atmospheric processes and phenomena of interest. Model deficiencies, and especially model systematic errors, represent a severe limit in this sense and the cooperation with the WWRP - Mesoscale Weather Research Forecasting Working Group is important to support model developments and to asses predictability of “small scale” phenomena. The recent development of Ensemble Based Data Assimilation technology represents one of the most demanding subject for cooperation.

Even if High-Impact Weather is not always necessarily Severe Weather (e.g. moderate hazard in a high impact area) this is the case for most of the events. This aspect makes statistical evaluations of EPS forecasting skill quite tricky due to several reasons as the poor availability of suitable observational data-sets and the fiddly properties of some parameters, precipitation in primis. To this purpose the cooperation with the Joint WG on verification is crucial. The further necessity to evaluate the importance of LAM EPS by considering the perception of product value by the forecasters, the end users and the decision makers, leads to the establishment of cooperation with the SERA WG. This cooperation will also facilitate the development of new and more satisfactory tools to communicate probabilistic information.

6.9 Action 9: Set up of specific cooperation initiatives, research projects, and demonstration project

As already emphasized several times, a regional approach is critical to ensuring positive outcomes from TIGGE-LAM. Regions should strive to take advantages of regional specificities and opportunities provided by available global models and EPS to provide initial and boundary conditions, specific high resolution observational networks, already existent agreements and cooperations etc. The regional approach is also essential to tailor the scientific objectives to the specific type of HIW.

Following the GIFS-TIGGE approach, RDPs and FDPs may be the best way to allow a coordinated work on LAM EPS on a regional basis and focussed on the specific HIW types. RDP and FDP constitute a perfect framework to cooperate among the different WMO WWRP working Groups.

The different realization of the SWFDP is also an important opportunity to introduce in an operational environment new products.

Research during RDPs should allow to develop and test the different components of the forecasting system: deterministic forecasts including data assimilation, EPS Global and LAM, combined and calibrated products. This approach is a good way to have a wide WWRP cooperation to advance mesoscale forecasting by exploiting all the best available modelling tools and by assessing the best way to combine them. RDPs are also important to tailor model outputs to user needs. Another relevant aspect of research during RDPs is the possibility to support the development of LAM EPS eventually based on the “relocation” of systems already running and tested over different regions even with different climatology and HIW phenomena.

Ongoing related activities

North America EPS test Bed (http://www.dtcenter.org)

The National Oceanic Atmospheric Administration (NOAA) has established the Hydrometeorological Testbed (HMT) to design and support a series of field and numerical modelling experiments to better understand and forecast precipitation in the Central Valley of California. The main role of the Forecast Application Branch (NOAA/ESRL/GSD) in HMT has been in supporting the real time numerical forecasts as well as research activities targeting better understanding and improvement of Quantitative Precipitation Forecasts (QPF). For this purpose ensemble modelling system has been developed. The ensemble system consists of mixed dynamic cores, mixed physics and mixed lateral boundary conditions.

HyMEX

The HYdrological cycle in the Mediterranean EXperiment, is a project endorsed by WWRP/Thorpex. HyMeX aims at a better understanding, quantification and modelling of the hydrological cycle in the Mediterranean, with emphasis on the predictability and evolution of extreme weather events.

TIGGE LAM EPS is contributing to the planning of this experiment and, particularly, to the Task: TTM1-a High-resolution ensemble hydrometeorological modelling for quantification of uncertainties. The aim of this Task Team is to identify the main sources of uncertainty in hydrometeorological forecasting systems, and design ensemble generation strategies that better represent them in the forecasting system. This will mainly consist of developing, setting-up and evaluating high-resolution ensemble hydro-meteorological modelling systems, and studying the downscale propagation of these uncertainties from the atmospheric down to the hydrological forecasts.

Another very relevant aspect of the HYMEX activity is the link between LAM EPS and Data Assimilation which will be developed through the implementation of a common testbed (*Wulfmeyer et al. 2011a*). This initiative will allow to initiate a closer cooperation between the Mesoscale Research Working Group and the (TIGGE-)LAM EPS community.

FROST-2014: Forecast and Research in the Olympic Sochi Testbed

FROST will include both FDP and RDP. FROST scientific activities will be focused to:

- Improve and exploit:
  - mesoscale forecasts of meteorological conditions in complex terrain environment;
  - regional EPS forecast products;
  - nowcasts of high impact weather phenomena in complex terrain;
- Improve understanding of physics of high impact weather phenomena in the region;
- Deliver forecasts in real time to Olympic forecasters and decision makers and quantify benefits of forecast improvement.

Convective Scale (1km) multi-model ensemble will be exploited during the RDP.

Both the MWFR WG and the Verification WG are strongly involved in the scientific planning of the project and TIGGE LAM is also contributing in strong cooperation with these WGs.

The Project scientific and technical management is structured over four Working Groups.
WG1: Observations and nowcasting (including Verification)
WG2: NWP, ensembles and assimilation (including Verification)
WG3: IT including graphical tools, formats, archiving and telecommunication
WG4: Products, training, end user assessment and social impacts

Europe: EurEPS

A new SRNWP Programme, EurEPS, is under submission by the SRNWP Expert Team on Predictability and EPS. In the Roadmap for the Forecasting Capability Area of EUMETNET the creation of a Eur-EPS Programme is envisaged.

This Programme should support a major cooperative effort to develop a capability for convection-permitting ensembles in order to address prediction of severe or high-impact weather in a probabilistic framework.

EurEPS will be structured in two phases:

- Phase I is proposed to be carried out in 2013, in order to identify properly all the needed technical facility, the requirements for Research and Development to design properly this innovative kind of systems and the potential framework for running the Phase II as a demonstration project

- Phase II would be executed over a 4-year time frame (2014–2017) as a demonstration project

The project proposal will be evaluated by EUMETNET in November 2011.

As a side initiative to this project, but valuable by itself even if EurEPS shouldn't be approved, is the **LAMEPS BC project** where a cooperation between ECMWF and the European LAM EPS group is ongoing to evaluate the best feasible support by ECMWF to LAM EPS activity in Europe. Several options are currently under investigation.

6.10 Action 10: Identification of possible funding opportunities to support the development and implementation of the regional activities

TIGGE LAM should stimulate contacts among the LAM EPS groups, and between the Panel and the other WWRP working groups, to investigate funding opportunities to support cooperating initiatives.

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ANNEX 1

TIGGE LAM Panel

Tiziana Paccagnella	ARPA-SIM / Italy	Chair
Tiziana Paccagnella (FP)	ARPA-SIM / Italy	TIGGE – LAM Panel Europe Sub-group
Jose A.Garcia Moya	INM / Spain	
Yong Wang	ZAMG / Austria	
Ken Mylne	MO / UK	
Trond Iversen	Univ Oslo /Norway	
Laurent Descamps	Meteo-France / France	
Marco Arpagaus	MeteoSwiss	
Andrea Montani	ARPA-SIMC	
Jan Barkmeier	KNMI	
Xiao Hua Yang	DMI	
Susanne Theis	DWD Germany	
Máté Mile	HMS Hungary	
Inger-Lise Frogner	Met.No	
Chiara Marsigli	ARPA-SIMC	
Josh Hacker (Focal Person)	UCAR / USA	TIGGE – LAM Panel N. America Sub-group
Brian Etherton	Renaissance Comput. Inst.	
Bill Gallus	Iowa State U.	
Fuqing Zhang	Penn State U.	
Ming Xue	Univ Oklahoma	
Xuguang Wang	U. of Oklahoma	
Ryan Torn	SUNY Albany	
Greg Hakim	Univ Washington / USA	
Brian Colle	SUNY Stonybrook	
Jun Du	NOAA/EMC	
Steve Mullen	Univ Arizona / USA	
Xuguang Wang	NOAA / USA	
Martin Charron	MS / Canada	
Isidora Jankov	CIRA, NOAA/ESRL	
Malaquais Pena	NOAA/EMC	
Jing Chen (Focal Person)	CMA / China	TIGGE – LAM Panel ASIA Sub-group
Jiandong Gong	CMA / China	
Vo Van Hoa	Vietnam Weather Service	
Kazuo Saito	Japan Met. Res. Institute	
Chou Sin Chan	CPTEC / Brazil	TIGGE – LAM Panel S. America Sub-group
Celeste Saulo	Univ. Buenos Aires	
Stephanie Landman	Weathersa South Africa	TIGGE – LAM Panel AFRICA Sub-group
Galebonwe Ramaphane	Botswana Weather Service	

ANNEX 2

TIGGE LAM parameters

Note: High Priority Parameters are listed in Bold

Reference documents:

FM 92 GRIB

(Edition 2 - Version 4 - 07/11/2007)

acronyms partly taken from ECMWF local tables

Table 1 - TIGGE LAM output parameters: single level

Parameter	Abbreviation	Level	Units written in the product definition section 4 (original variable without post-processing)	Freq	Prior	Other specifics	Present in TIGGE Global Archive	Comments
Mean sea level pressure	**msl**	**MSL (101)**	**Pa**	**3h**	**HP**	**Instantaneous Product Disc. 0 Param. Categ. 3 Param. n° 0**	**yes**	
Surface Pressure	**sp**	Surface (1)	Pa	3h		Instantaneous Product Disc. 0 Param. Categ. 3 Param. n° 0	yes	
10m U-velocity	**10u**	**10m (103,10)**	**m s-1**	**3h**	**HP**	**Instantaneous Product Disc. 0 Param. Categ. 2 Param. n° 2**	**yes**	
10m V-velocity	**10v**	**10m (103,10)**	**m s-1**	**3h**	**HP**	**Instantaneous Product Disc. 0**	**yes**	

						Param. Categ. 2 **Param. n° 3**		
Lifted index		Surface (1)	K	3h		Instantaneous **Parcel lifted Index (to 500 hPa)** Product Disc. 0 Param. Categ. 7 Param. n° 0 **Best lifted Index (to 500 hPa)** Product Disc. 0 Param. Categ. 7 Param. n° 1 **Surface lifted Index** Product Disc. 0 Param. Categ. 7 Param. n° 10		**Algorithm** **not defined yet**
Storm Relative Helicity	srhl	1-3km (103,1000) (103,3000)	J kg-1	3h		Instantaneous Product Disc. 0 Param. Categ. 7 Param. n° 8		
wind speed (gust)	**10fg3**	**10 m** **(103,10)**	**m s-1**	**3h**	**HP**	**Maximum over the period** **(last 3 hours for TIGGE LAM)** **Product Disc. 0** **Param. Categ. 2** **Param. n° 22** **typeOfStatisticalProcessing 2** **typeOfTimeIncrement 2** **indicatorOfUnitForTimeRange 1** **lengthOfTimeRange 3**		
Surface air temperature	**2t**	**1.25 to 2m**	**K**	**3h**	**HP**	**Instantaneous** **Product Disc. 0** **Param. Categ. 0**	**yes**	

						Param. n° 0		
Surface air dew point temperature	**2d**	**1.25 to 2m**	**K**	**3h**	**HP**	**Instantaneous** **Product Disc. 0** **Param. Categ. 0** **Param. n° 6**	**yes**	
Surface air max temperature **	**mx2t3**	1.25 to 2m	K	3h		Maximum over the period (last 3 hours for TIGGE LAM) Instantaneus Product Disc. 0 Param. Categ. 0 Param. n° 0 typeOfStatisticalProcessing 2 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Surface air min temperature **	**mn2t3**	1.25 to 2m	K	3h		Minimum over the period (last 3 hours for TIGGE LAM) Product Disc. 0 Param. Categ. 0 Param. n° 0 typeOfStatisticalProcessing 3 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Skin Temperature	**skt**	surface	K	3h		Instantaneous Product Disc. 0 Param. Categ. 0 Param. n° 17	yes	
Planetary Boundary Layer height	**blh**	1	m	3h		Instantaneous Product Disc. 0 Param. Categ. 3 Param. n° 18		

large scale precipitation						Accumulated since start of the forecast (TIGGE standard) Product Disc. 0 Param. Categ. 1 Param. n° 54		
Total precipitation (liquid + frozen)	**tp**	**surface**	**kg m-2 s-1 (Total precipitation rate)**	**3h**	**HP**	**Accumulated since start of the forecast (TIGGE standard)** **Product Disc. 0** **Param. Categ. 1** **Param. n° 52**	**yes**	
ICE COVER (sometime referred to as sea ice)	IC	surface	proportion (values between 0 and 1)	3h		Instantaneus Product Disc. 10 Param. Categ. 2 Param. n° 0		
Total Snowfall water equivalent	**sf**	surface	kg m^{-2} s^{-1} (Total Snowfall rate water equivalent)	3h		Accumulated since start of the forecast (TIGGE standard) Product Disc. 0 Param. Categ. 1 Param. n° 53	yes	
Snow depth water equivalent	**sd**	surface	kg m^{-2}	3h		Instantaneous Product Disc. 0 Param. Categ. 1 Param. n° 60	yes	
Sea surface temperature (water temperature at the surface)	sst	surface	K	3h		Instantaneous Product Disc. 10 Param. Categ. 3 Param. n° 0		
Soil moisture	**sm**	top 20cm typeOfLevel 106	kg m-3	3h		Instantaneous Product Disc. 2	yes	

		(106,0) (106,0.2) scale factor F scaled value V original value L a: $L * 10^{FF} = V$				Param. Categ. 0 Param. n° 22		
Wilting point	**wilt**	top 20cm typeOfLevel 106 (106,0) (106,0.2) scale factor F scaled value V original value L a: $L * 10^{FF} = V$	kg m-3	3h		Control run Instantaneous Product Disc. 2 Param. Categ. 0 Param. n° 26	yes	
Transpiration stress – onset (Field capacity?)	**cap**	top 20cm typeOfLevel 106 (106,0) (106,0.2) scale factor F scaled value V original value L a: $L * 10^{FF} = V$	kg m-3	3h		Control run Instantaneous Product Disc. 2 Param. Categ. 3 Param. n° 12	yes	
Soil temperature	**st**	top 20cm typeOfLevel 106	K	3h		Instantaneous Product Disc. 2	yes	

		(106,0) (106,0.2) scale factor F scaled value V original value L a: L * 10^{FF} = V				Param. Categ. 0 Param. n° 2		
Total cloud cover	**tcc**	surface	0-100%	3h		Instantaneous Product Disc. 0 Param. Categ. 6 Param. n° 1	yes	
Cloud base	**cb**	surface	m	3h		Instantaneous Product Disc. 0 Param. Categ. 6 Param. n° 11		
Visibility	vis	surface	m	3h		Instantaneous Product Disc. 0 Param. Categ. 19 Param. n° 0		
Total column water	**tcw**	surface	kg m-2	3h		Instantaneous Product Disc. 0 Param. Categ. 1 Param. n° 51	yes	
Time Integrated Surface Latent Heat Flux,	**slhf**	surface	W m^{-2}	3h		Accumulated Product Disc. 0 Param. Categ. 0 Param. n° 10 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1	yes	

						lengthOfTimeRange 3		
Time Integrated Surface sensible heat flux	**sshf**	surface	W m^{-2}	3h		Accumulated Product Disc. 0 Param. Categ. 0 Param. n° 11 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Time integrated surface Net Short Wave radiation flux	**ssr**	surface	W m^{-2} Net Short Wave Radiation Flux	3h		Accumulated Product Disc. 0 Param. Categ. 4 Param. n° 9 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Time integrated Surface Net Long Wave (Thermal) radiation flux	**str**	1 (surface)	W m^{-2} Net Long Wave Radiation Flux	3h		Accumulated Product Disc. 0 Param. Categ. 5 Param. n° 5 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Time integrated net Long Wave radiation	**ttr**	8 (top of the atmosphere)	W m^{-2} Net Long Wave Radiation Flux	3h		Accumulated Product Disc. 0 Param. Categ. 5 Param. n° 5 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2	yes	

						indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3		
Sunshine duration	**sund**	surface	sec	3h		Accumulated Product Disc. 0 Param. Categ. 6 Param. n° 24 typeOfStatisticalProcessing 1 typeOfTimeIncrement 2 indicatorOfUnitForTimeRange 1 lengthOfTimeRange 3	yes	
Convective available potential energy	**cape**	1 (vertical integrated)	J kg-1	3h		Instantaneous Product Disc. 0 Param. Categ. 7 Param. n° 6	yes	
Convective inhibition	cin	1 (vertical integrated)	J kg-1	3h		Instantaneous Product Disc. 0 Param. Categ. 7 Param. n° 7	yes	Sample extracted form NCEP dataset
Orography (Geopotential height at the surface)	**orog**	surface	gpm	3h		Instantaneous Control run Product Disc. 0 Param. Categ. 3 Param. n° 5	yes	
Land-sea mask	**lsm**	surface	proportion (values between 0 and 1)	3h		Instantaneous Control run Product Disc. 2 Param. Categ. 0 Param. n° 0	yes	

*** productDefinitionTemplateNumber=11 (not at a specific time but in a continuous or non-continuous interval)*

Table 2 - TIGGE LAM output parameters: Potential Temperature level

Potential Vorticity (theta=320 for clarity)	**pv**	(107,320)	$K\ m^2\ kg^{-1}\ s^{-1}$	3h		Instantaneous Product Disc. 0 Param. Categ. 2 Param. n° 14	yes	

Table 3 - TIGGE LAM output parameters: Potential Vorticity level

Potential Temperature (PV=2 for clarity)	pt	(109,2e-06) coded as (109,2) scale factor F=6 scaled value V=2 original value L a: $L * 10^{FF} = V$	m s-1	3h		Instantaneous Product Disc. 0 Param. Categ. 0 Param. n° 2	yes	
U-velocity (PV=2 for clarity)	u	(109,2e-06) coded as (109,2) scale factor F=6 scaled value V=2 original value L a: $L * 10^{FF} = V$	m s-1	3h		Instantaneous Product Disc. 0 Param. Categ. 2 Param. n° 2	yes	
V-velocity (PV=2 for clarity)	v	(109,2.e-06) coded as	m s-1	3h		Instantaneous Product Disc. 0 Param. Categ. 2	yes	

		(109,2) scale factor F=6 scaled value V=2 original value L a: $L * 10^{FF} = V$				Param. n° 3		

Table 4 - TIGGE LAM output parameters: pressure levels

Parameter	Name	Level	Units written in the product definition section 4 (original variable without post-processing)	Freq	Prior	Other specifics	TIGGE Global	Comments
Temperature	t	(100,100000) (100,92500) (100,85000) (100,70000) (100,50000) (100,30000) (100,25000)	K	6h		Instantaneous Product Disc. 0 Param. Categ. 0 Param. n° 0	yes	
Geopotential height	gh	(100,100000) (100,92500) (100,85000) (100,70000) (100,50000) (100,30000) (100,25000)	gpm	6h		Instantaneous Product Disc. 0 Param. Categ. 3 Param. n° 5	yes	
U-velocity	u	(100,100000) (100,92500) (100,85000) (100,70000)	m s-1	6h		Instantaneous Product Disc. 0 Param. Categ. 2	yes	

		(100,50000) (100,30000) (100,25000)				Param. n° 2		
V-velocity	v	(100,100000) (100,92500) (100,85000) (100,70000) (100,50000) (100,30000) (100,25000)	m s-1	6h		Instantaneous Product Disc. 0 Param. Categ. 2 Param. n° 3	yes	
Specific Humidity	q	(100,100000) (100,92500) (100,85000) (100,70000) (100,50000) (100,30000) (100,25000)	Kg kg-1	6h		Instantaneous Product Disc. 0 Param. Categ. 1 Param. n° 0	yes	

- ☐ **5 parameters on 7 pressure levels: 1000, 925, 850, 700, 500, 300, 250 hPa**

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, WWRP/THORPEX No. 14.

15. Targeted Observations for Improving Numerical Weather Prediction: An Overview. WWRP/THORPEX No. 15.

16. International Core Steering Committee for THORPEX. Ninth Session 21-22 September 2011, Geneva, Switzerland. WWRP/THORPEX No. 16.

17. THORPEX Interactive Grand Global Ensemble Limited Area Model Plan (TIGGE LAM), WWRP/THORPEX No. 17.