THORPEX

A Global Atmospheric Research Programme

International Science Plan

Melvyn Shapiro
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Commission for Atmospheric Sciences

THORPEX International Science Steering Committee

Version 3
2 November 2004

World Weather Research Programme

World Meteorological Organization
Weather • Climate • Water

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Version III: 2 November 2004

Melvyn A. Shapiro[2] and Alan J. Thorpe[3]

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[1] This Science Plan is dedicated to the memory of our friend and colleague Hajime Nakamura.

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Preface

THORPEX: a **G**lobal **A**tmospheric **R**esearch **P**rogramme for the 21^{st} Century

THORPEX is an international research programme to accelerate improvements in the accuracy of 1-day to 2-week high-impact weather forecasts. These improvements will lead to substantial benefits for humanity, as we respond to the weather related challenges of the 21^{st} century. THORPEX research Sub-programmes address: i) global-to-regional influences on the evolution and predictability of weather systems; ii) global observing-system design and demonstration; iii) targeting and assimilation of observations; iv) societal, economic, and environmental benefits of improved forecasts. THORPEX establishes an organisational framework that addresses weather research and forecast problems whose solutions will be accelerated through international collaboration among academic institutions, operational forecast centres and users of forecast products.

The THORPEX International Science Plan:

- Provides the rationale and research agenda for THORPEX by identifying opportunities leading to advances in weather research and forecasting over the next decade

- Defines the goals of THORPEX within the scope of its four research Sub-programmes

- Establishes the foundation for the development of the THORPEX International Research Implementation Plan

A series of reports on THORPEX will be published that build upon the current definition of the programme, as the research objectives evolve and roadmaps for their implementation emerge.

The Science Plan is currently under a peer-review process, organized by the CAS Science Steering Committee for the World Weather Research Programme.

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1. Introduction

1.1 Rationale

The success of numerical weather prediction represents one of the most significant scientific, technological and societal achievements of the 20th century. Despite the notable increase in forecast skill over the past quarter century (Fig.1.1), there is a necessity for further improvements, particularly, in the accuracy of high-impact weather forecasts and in the use of weather forecast information. High-impact weather forecasts are defined by their effect on society, the economy and the environment. They are typically associated with forecasts of cyclones of extratropical and tropical origin that contain significant embedded mesoscale weather and its impacts. These include localized flooding by convective and orographic precipitation; blizzard snows; dust-storms; destructive surface winds (Fig.1.2). They also encompass forecasts of meteorological conditions affecting air quality, periods of anomalous high/low temperature, drought, and non-extreme weather with high societal/economic impact. Many of these events are characterised as low probability, but with high risk, in that the event is unlikely, but the consequences of occurrence may be catastrophic. Improving the skill of high-impact weather forecasts is one of the great scientific and societal challenges of the 21st century. THORPEX responds to this challenge.

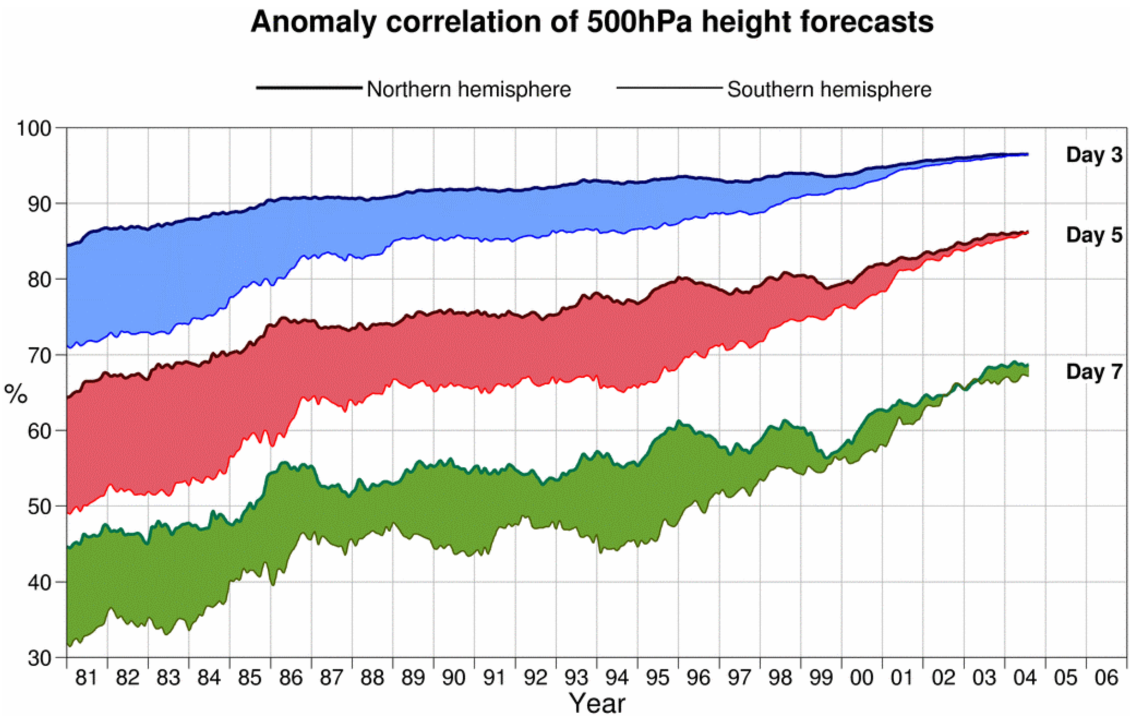

Fig. 1.1: Evolution of forecast skill for the northern and southern hemispheres: 1980-2004. Anomaly correlation coefficients of 3, 5, and 7-day ECMWF 500-mb height forecasts for the extratropical northern and southern hemispheres, plotted in the form of running means for the period of January 1980-August 2004. Shading shows differences in scores between hemispheres at the forecast ranges indicated (from Hollingsworth, *et al*. 2002).

Recent developments in atmospheric science and technology provide the opportunity for further improvements in the accuracy of high-impact weather forecasts and in their use and value to society. These developments include: i) advances in knowledge of the theoretical and practical limits of atmospheric predictability, including the influence of inter-annual and sub-seasonal climate variability on forecast skill; ii) expanding observations of the Earth

System with satellite, airborne, marine and land-based observing technologies; iii) weather forecast systems capable of assimilating observations from the above diverse technologies; iv) advanced forecast procedures aided by improvements in numerical techniques, parameterised and explicit representations of physical processes, ensemble forecast techniques, and exponential increases in the speed and memory of supercomputers; v) innovative approaches to the design and implementation of forecast systems that will advance the societal and economic utilisation of weather information. In the same way that the atmosphere encompasses the globe, the expertise to exploit and further these advances resides across many nations, international organisations, and diverse scientific disciplines. During the years ahead, new technologies, scientific paradigms, forecast systems, and societal/economic application strategies will emerge, as they have in the past, presenting significant opportunities. THORPEX will adapt its research to capitalise on these opportunities.

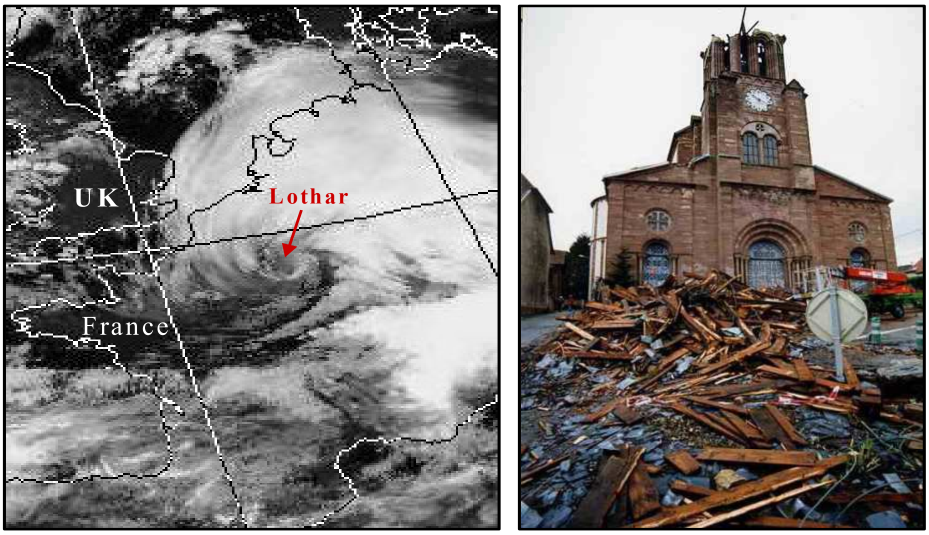

Fig. 1.2: The societal and economic impact of the ~150 km h^{-1} surface winds associated with extratropical cyclone "Lothar". *Left*: Dundee Satellite Station infrared image of Lothar at 0754 UTC 26 December 1999. *Right*: Lothar's destruction of the church in Balliveirs, France (courtesy of Emmanuel DeBraize)

THORPEX establishes a contemporary organisational framework to address global weather research and forecast problems whose solutions require international collaboration among academic institutions, operational forecast centres, and users of forecast information. This includes engagement with other international programmes within the World Meteorological Organisation (WMO), the International Council of Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC). In this regard, THORPEX aspires to be the second Global Atmospheric Research Programme (GARP); building on the accomplishments of the First GARP Global Experiment (FGGE) during the 1960s and 70s.

THORPEX is developed and implemented as a part of the WMO World Weather Research Programme (WWRP). International co-ordination for THORPEX is established under the auspices of the WMO Commission for Atmospheric Sciences (CAS) through its Science Steering Committee for the WWRP, and joint CAS/JSC Working Group on Numerical Experimentation (WGNE). The THORPEX International Science Steering Committee (ISSC) develops the core research objectives with guidance from the THORPEX International Core Steering Committee (ICSC) whose members are nominated by Permanent Representatives of countries with the WMO. Research objectives are developed under four

Sub-programmes: *Predictability and Dynamical Processes*; *Observing Systems*; *Data Assimilation and Observing Strategies*; *Societal and Economic Applications*. These Sub-programmes have the responsibility to: i) coordinate the research activities envisaged in the THORPEX International Science and Implementation Plans; ii) collaborate with other international programmes when relevant expertise is required and mutual benefit is derived. Nations and consortia of nations have established THORPEX Regional Committees that define regional priorities for participation in THORPEX within the framework of the THORPEX International Science and Implementation Plans.

THORPEX core objectives:

- Increase knowledge of global-to-regional influences on the initiation, evolution and predictability of high-impact weather. This objective includes research on: i) the excitation of Rossby wave trains by extratropical cyclone development, large-scale topography, continent/ocean interfaces, organised tropical and extratropical convective flare-ups**,** and the role of these processes in the consequent development of high-impact weather; ii) the dependence of predictive skill on inter-annual and sub-seasonal climate variability, e.g., El Niño Southern Oscillation (ENSO); Pacific North-Atlantic oscillation (PNA); North-Atlantic Oscillation (NAO); Arctic Oscillation (AO); monsoon circulations; iii) the relative contribution to the limits of predictive skill by uncertainty in observations, data assimilation, model formulation and ensemble prediction system design.

- Contribute to the design and demonstration of *interactive forecast systems* that allow information to flow interactively among forecast users, numerical forecast models, data-assimilation systems and observations to maximise forecast skill. As an example, targeted observing strategies incorporate dynamical information from the numerical forecast model itself to identify when, where, and what types of observations would provide the greatest improvement to specific weather forecasts of societal, economic, and environmental interest.

- Contribute to the development of advanced data assimilation and ensemble prediction systems. This effort will include: i) improving the assimilation of existing and experimental observations, including observations of water in its three phases and atmospheric composition (e.g., ozone; aerosols); ii) developing adaptive data assimilation and targeted-observing strategies; iii) incorporating model uncertainty into data-assimilation systems and in the design of ensemble prediction systems; iv) evaluating the utility of multi-model ensemble prediction systems.

- Develop and apply new methods that enhance the utility and value of weather forecasts to society, economies and environmental stewardship through: i) user-specific probabilistic forecast products; ii) the introduction of interactive procedures that make the forecast system more responsive to user needs; iii) the design of and training in the use of user-specific forecast products. Research will identify and assess the societal/economic costs and benefits of THORPEX recommendations for implementing interactive forecast systems and improvements in the global observing system.

- 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. They are organised and coordinated by regional consortia of nations under THORPEX Regional Committees, e.g., Europe; Asia; North and South America; Southern Hemisphere. TReCs address forecasts of regional weather systems, e.g., arctic storms and cold-air outbreaks; extratropical cyclones over Europe, Asia, and North America; warm-season heavy precipitation over Asia; organized equatorial convection flare-ups; tropical-to-extratropical cyclone transformations. TReCs require collaboration between Regional Committees. THORPEX will explore the opportunities to carry out TReCs in conjunction with major international programmes such as the International Polar Year (IPY) and the African Monsoon Multi-disciplinary Analysis (AMMA).

- 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. This includes the *THORPEX Interactive Grand Global Ensemble* (TIGGE) that integrates developments in observing systems, targeting, adaptive data assimilation, model improvements, forecast user requirements, and a multi-model/multi-analysis ensemble prediction system.

- Coordinate THORPEX research with the World Climate Research Programme: Coordinated Observation and Prediction of the Earth System (WCRP/COPES) and the mesoscale/microscale community to address the observational and modelling requirements for the prediction of weather and climate for two weeks and beyond.

- 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.

THORPEX is unique, in that:

- It establishes an organisational framework to address today's global weather research and forecast problems whose solutions require international collaboration between academic institutions, operational forecast centres, and users of forecast information**.** Its research domain spans global-to-regional influences on high-impact weather forecasts.

- It has at its heart the contemporary paradigm in which weather forecasting is an interactive process, with information flowing between forecast users, forecast models, data assimilation and global and regional observing systems.

- It addresses the influence inter-annual and sub-seasonal atmospheric and oceanic variability on high-impact forecasts out to two weeks, and therefore aspires 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.

- It will 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.

1.2 Reference Material

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2. Predictability and Dynamical Processes Research

2.1 Rationale

Questions are often posed regarding the spatial and temporal limits of predictability, and what determines these limits. The limits of predictability depend on the properties of the atmosphere that are being forecast, because different properties of the atmospheric circulation exhibit differing degrees of predictability over particular time ranges. For example: i) the global-mean surface temperature exhibits predictability over time-scales in excess of centuries; ii) monthly-mean temperatures over particular regions have some predictive skill from seasons to decades; iii) individual synoptic-scale weather systems are predictable out to ~8 days; iv) sub-synoptic scale systems, whose predictability ranges from a few days for fronts down to hours or less for sub-mesoscale cloud elements within organized meso-convective systems.

THORPEX predictability and dynamical-processes research will address those aspects of the atmosphere, ocean, and land, and numerical forecast systems that contribute to limitations in the predictive skill of high-impact forecasts ranging from one-day to two-weeks. The scientific approach is derived from fundamental predictability studies (e.g., Lorenz 1963; Leith and Kraichnan 1972) which established that the growth of uncertainty, and hence the limit of predictability in chaotic dynamical systems, was attributable to the two-way cascade of energy between the slowly evolving large-scale circulations, and the smaller-scale, shorter-lived, resolved and unresolved motions. From an atmospheric predictability perspective, the downscale cascade of energy and enstrophy from planetary-scale circulations acts to organize the synoptic-scale and mesoscale flows most typically associated with high-impact weather and its prediction. The mesoscale circulations, in turn, provide energy for the growth of the smaller motions, culminating in turbulent dissipation in the free atmosphere and at the earth's surface. An example of the down-scale cascade of energy is when equatorial heating over eastern Pacific Ocean, during the warm-phase of ENSO, modulates the extratropical zonal time-mean flow, which in turn impacts the life cycles of extratropical cyclones, including their internal sub-synoptic structures (Section 2.2).

A key element that contributes to the limit of predictability is the up-scale cascade of energy from parameterised and unresolved processes to the large-scale motions. Small-scale perturbations, arising from errors in the representation of these processes grow and nonlinear interactions permeate the large-scale motions as the forecast lead-time increases, eventually limiting predictability on the larger-scales. These small-scale processes include: i) deep and shallow moist convection; ii) boundary-layer and surface-exchange; iii) clouds and radiation; and iv) inertia gravity wave breaking over mountains, within jet-stream/frontal-zone systems, and convective cloud systems that interact with the tropopause. THORPEX will address the role of up-scale energy cascade on the life cycles of synoptic-scale and planetary-scale weather systems and their predictability. This will require collaborations with the mesoscale/microscale research community, whose ongoing advances in: i) physical process parametrizations and their explicit representation; ii) observation and diagnosis of physical processes derived from field campaigns, are key elements in the quest to improve forecast skill at time ranges out to week-two and beyond.

In summary, THORPEX Predictability and Dynamical Process Research will assess the various factors that contribute to current limits of predictability for appropriate forecast attributes, and through this determination, develop and demonstrate new dynamical interpretations, and observing-systems and forecasting strategies that will extend these limits.

2.2 Dynamical Process Research

THORPEX dynamical processes research strives to advance knowledge of the global-to-regional influences on the evolution and predictability of high-impact weather. A basic premise is that there exists a class of regional weather events and their forecasts that develop within the context of the larger-scale motions. These include: i) extratropical cyclones, whose tracks and forecast skill are modulated by anomalies in inter-annual and sub-seasonal time-mean flows; ii) extratropical cyclones that form by downstream baroclinic development associated with larger-scale Rossby wave trains (wave packets) shown in Figs. 2.1.and 2.2; iii) fronts and their associated mesoscale precipitation systems that form in response to synoptic-scale deformations; iv) organised mesoconvective precipitation systems that form where the synoptic-scale flow brings together contrasting air masses, such as at the Mei-Yu (Baiu) front, arctic front, and eastern North-Atlantic "Spanish plume"; v) tropical cyclones and their transformation into extratropical cyclones through interactions with synoptic-scale waves in the extratropical westerlies (Jones *et al.* 2003); vi) sub-tropical cyclones that transition into late season tropical cyclones through interactions with extratropical baroclinic waves (Davis and Bosart 2003). Research will also address the evolution of sub-seasonal and inter-annual phenomena, so as to capture and exploit the significant dependence of the life cycles and predictive skill of high-impact weather on planetary-scale influences, such as, the phases of the MJO, NAO, AO, and ENSO (Fig. 2.3). This represents a major intersection between weather and climate prediction.

Examples of THORPEX dynamical processes research foci, discussed below, are: i) Rossby wave trains and their relationship to the propagation of forecast error and the complementary potential vorticity (PV) perspective; ii) the initiation and maintenance of large-scale organised tropical convection and its influence on tropical and extratropical forecast skill.

***Rossby wave trains*:** The excitation and dispersion of Rossby wave trains is an example of the global propagation of a localized influence on high-impact weather and its prediction. The skilful prediction of Rossby wave-train activity is often a requisite for forecasting the synoptic-scale setting within which smaller-scale, high-impact weather events evolve at forecast time ranges out to two weeks. Rossby wave trains are initiated by components of the flow, such as: i) downstream baroclinic development (Orlanski and Sheldon 1993); ii) the interaction of extratropical flows with large-scale topography, e.g., the Tibetan Plateau; Greenland (Fig. 2.4); iii) variations in moist tropical convective-heating associated with ENSO, MJO, and higher-frequency convective variability within the tropical oceanic convergence zones and monsoon regions. Other aspects of interest are: i) the establishment and maintenance of Rossby wave guides; ii) triggering of sub-synoptic scale features by individual synoptic waves within wave trains and their feed back into the dispersion of the wave train. The group velocity at which Rossby wave trains propagate is equivalent to the propagation velocity at which forecast errors spread downstream (upstream) from an initially localized region of initial-condition error. Both Rossby wave trains and forecast error can circumnavigate the hemisphere at 45^{o} N. in ~12 days (Chang and Yu 1999), as was the case for the wave train initiated by downstream baroclinic development in Figs. 2.1 and 2.2

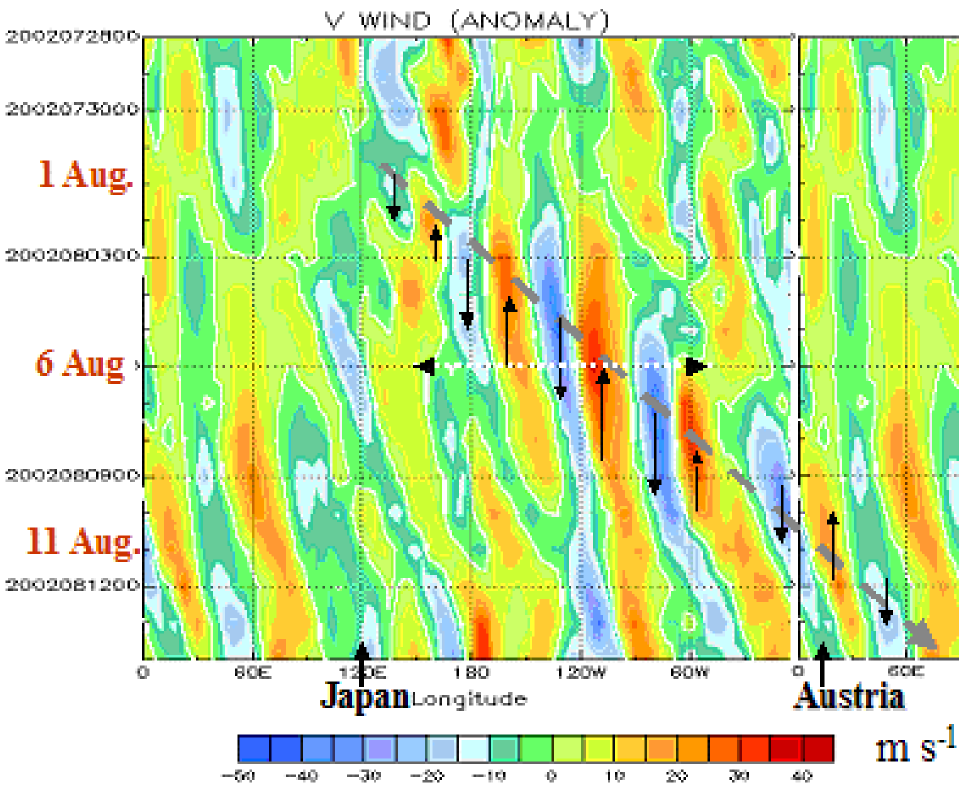

Fig. 2.1: Hovmöller (time-longitude) diagram of the 250-mb meridional wind component (ms^{-1}) for the period 28 July - 14 August 2002 and the latitudinal belt 40-60º N. Extreme flooding in central Europe occurred at the end of this period. On 1 August, a Rossby wave train was excited by cyclogenesis east of Japan, followed by rapid downstream development of high-amplitude Rossby waves that led to severe flooding in Europe on 11 August 2002. The white dashed line at 6 August indicates the longitude extent of the Rossby wave train in Fig. 2.2. A skilful forecast of the cyclogenesis east of Japan, and the subsequent Rossby wave dispersion, was necessary for a skilful medium-range forecast over Europe.

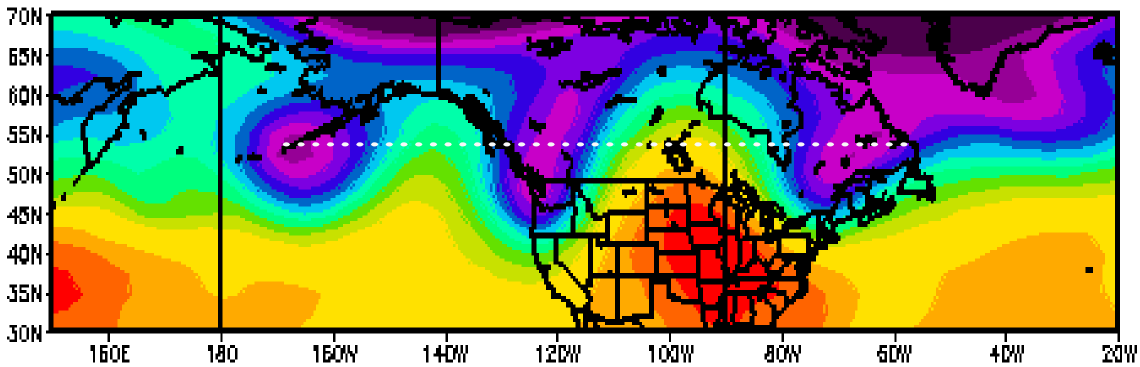

Fig. 2.2: Rossby wave train on 6 August 2002 (for Fig.2.1). 250-mb geopotential at 50-decameter intervals. White dashed line; ray path and longitudinal extent of the wave train.

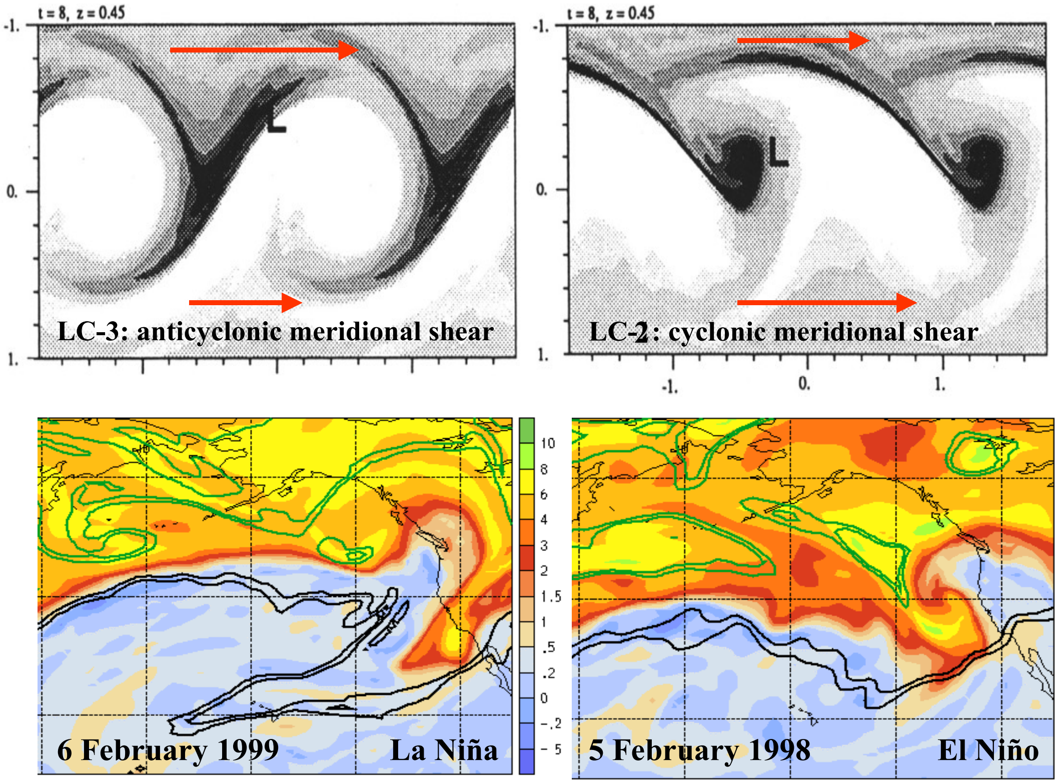

Fig. 2.3: Idealized and observed potential vorticity (PV) distributions illustrating the influence of differing planetary time-mean flows on Rossby wave breaking. ***Upper panels*****:** semi-geostrophic idealised simulations under the influence of anticyclonic (*left,* LC3) and cyclonic (*right,* LC2) time-mean meridional barotropic shear; PV > 1.5 PVU, shaded (from Davies *et al* 1991). ***Lower panels*****:** ECMWF observed potential vorticity (PV) at three isentropic levels for the cold and warm phases of ENSO, respectively; *(left*) 1200 UTC 6 February 1999 (La Nia); (*right*) 1200 UTC 5 February 1998 (El Niño). 300-K PV (green lines, 2 and 3 PVUs); 320-K PV (PVU, shaded colour bar); 340-K PV (black lines, 2 and 3 PVUs). During the period 16 January-28 February 1998 and 1999, tropopause-based PV life cycles over the eastern North Pacific were dominated by cyclonic and anticyclonic Rossby wave breaking, respectively (from Shapiro *et al*. 2001).

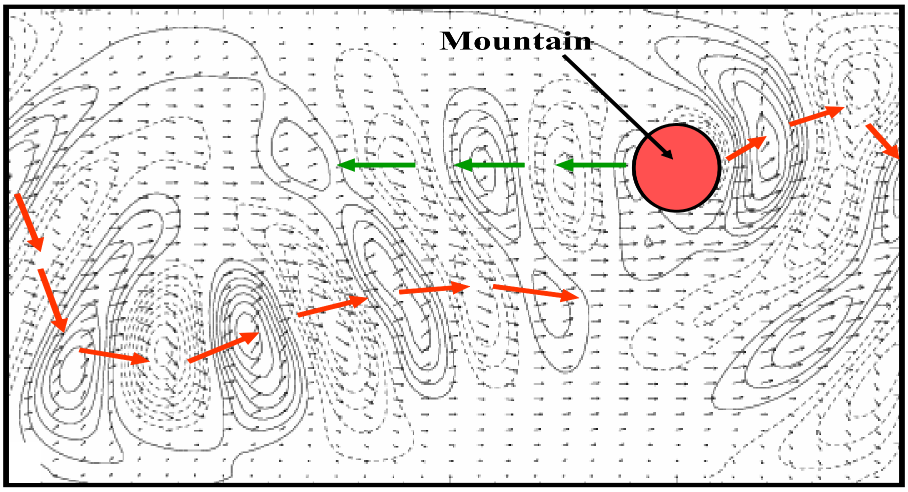

Fig. 2.4: Idealised simulation of planetary wave train excitation on a sphere by an equatorial, westerly, barotropic jet impinging upon a 2-km high by 2,000-km diameter conical mountain (red circle). Contours show patterns of meridional velocity components in ms^{-1}, with imposed flow vectors at 4 km after 15 days of simulation. Negative values are dashed; red and green coloured arrows denote downstream and upstream wave-train ray-paths, respectively (from Smolarkiewicz, *et al.* 2001).

***The potential vorticity perspective*:** Potential vorticity (PV) distributions characterize those quasi-balanced dynamical features that are most potent in the development of synoptic-scale weather systems. The PV perspective is useful for identifying and tracking *centres of action* because of its various dynamical properties: i) conservation (in certain cases); ii) non-conservation due to irreversible physical processes; iii) invertibility. The use of *conservation* and *invertibility* to infer the dynamics of quasi-balanced flows is known as *PV thinking*. Diagnosing forecast-model behaviour in terms of PV can be a powerful tool for isolating key uncertainties in the representation of dynamical and physical processes, when the magnitude of the PV uncertainty is sufficiently large relative to the background PV. Recent studies (e.g., Reynolds *et al.* 2001) suggest that certain types of initial-condition uncertainties, associated with appreciable forecast error growth, are up-shear-tilted PV structures that are initially maximized in the lower to mid-troposphere, with magnitudes comparable to typical variations in the tropospheric PV. Research issues to be addressed using PV diagnosis include: i) the extratropical transition of tropical cyclones; ii) the PV structure of singular vectors and other growing perturbations; iii) the PV perspective of Rossby wave trains; iv) flare-ups of tropical convection associated with Rossby wave energy and associated PV perturbations propagating from the extratropics into low latitudes (Kiladis 1998). There is a strong complementarity between Rossby wave and PV perspectives.

Organised tropical convection and its influence on global forecast skill: Moist tropical convection has a propensity to organize upscale and to display variability on time scales ranging from a few days to sub-seasonal. A notable example is the Madden-Julian Oscillation (MJO) that involves the interaction between localised organised moist convection and the tropical atmospheric and oceanic circulation. It is likely that the limited accuracy of current convective parametrizations contributes to limitations in forecast skill in the tropics on all time scales, and in the extratropical latitudes at the medium range and beyond. As an example, Fig. 2.5 shows the week-two (8-14 day) forecasts of precipitation (*right panel*) and 3-day running mean verification observations of outgoing long-wave radiation, a proxy for deep convection (*left panel)* using a dataset from Hamill *et al*. (2004). The colour shading (*left panel*) indicates the cold cloud-top temperatures associated with the deep moist convection during ~1-month periods of the MJO active phase (solid blue contours). Note the individual convective flare-ups of ~1-week duration (orange-to-red shading) embedded within the ~1-month duration MJO convective envelopes (yellow-to-red shading). The observed convective organization seen in the left panel is absent in the precipitation forecasts shown on the right.

It is argued that the skill of extended-range weather and climate prediction will benefit from improved representation of the initiation and maintenance of organised tropical convection. The success of advanced parametrizations in idealised simulation models in generating MJO-like organised convective systems and their internal shorter time scale convective flare-ups, (Fig.2.6) provides the prospect that the required advances in parameterisation within operational forecast systems are within sight (e.g., Grabowski 2001; Moncrieff 2004). The improved representation of organised mesoscale convection within operational global prediction models is one of the prerequisites for improved prediction out to sub-seasonal time scales and possibly beyond. As a first test, it is of interest to determine if observed organised tropical convective flare-ups (Fig. 2.5) can be simulated with high-resolution cloud-resolving mesoscale models over a suitably large tropical domain, including two-way interactive boundaries between the mesoscale and global models to allow for the propagation localised tropical convective heating into the mid-latitude baroclinic wave guide. Recent results from experimental daily predictions over the central US with regional cloud-resolving models (Fig.2.7) have demonstrated the capability to initiate and sustain organised mesoconvective systems for up to 9 days of simulation, with exceptional realism compared to observations by Carbone *et al.* 2002. Tropical convective flare-ups have important influences on extratropical circulations, particularly regarding their initiation and or amplification of dispersive Rossby wave trains that impact upon extratropical baroclinic life cycles and their predictability (Fig. 2.8). Mesoscale convective organization is an important process for other types of large-scale convective variability, such as convective flaring of the inter-tropical convergence zone (ITCZ), convectively coupled Kelvin waves, and extratropical mesoscale-convective convective systems.

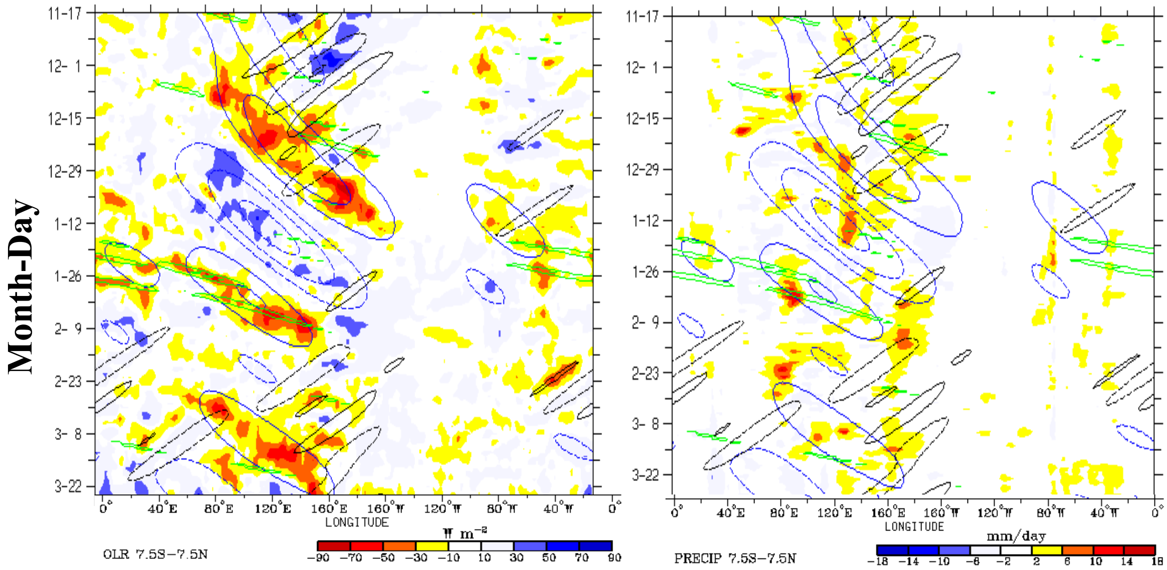

Fig. 2.5: left panel: 3-day running mean anomalies of observed outgoing long-wave radiation (OLR) for the latitudinal belt 7.5N-7.5 S from 17 November 2003 through 23 March 2004; *right panel*: week-2 (days 8-14) forecasts of precipitation anomalies from a 1998 version of NCEP's Medium Range Forecast model. The colour bars show units and shading levels. The line contours are time-space filtered observed OLR anomalies and define three different convectively coupled tropical modes (Wheeler and Kiladis, 2000). The blue contours slanting downward from left to right represent the Madden Julian Oscillation, the green contours represent the Kelvin wave and the black contours slanting from right to left represent the equatorial Rossby wave (courtesy of Klaus Weickmann NOAA/CDC).

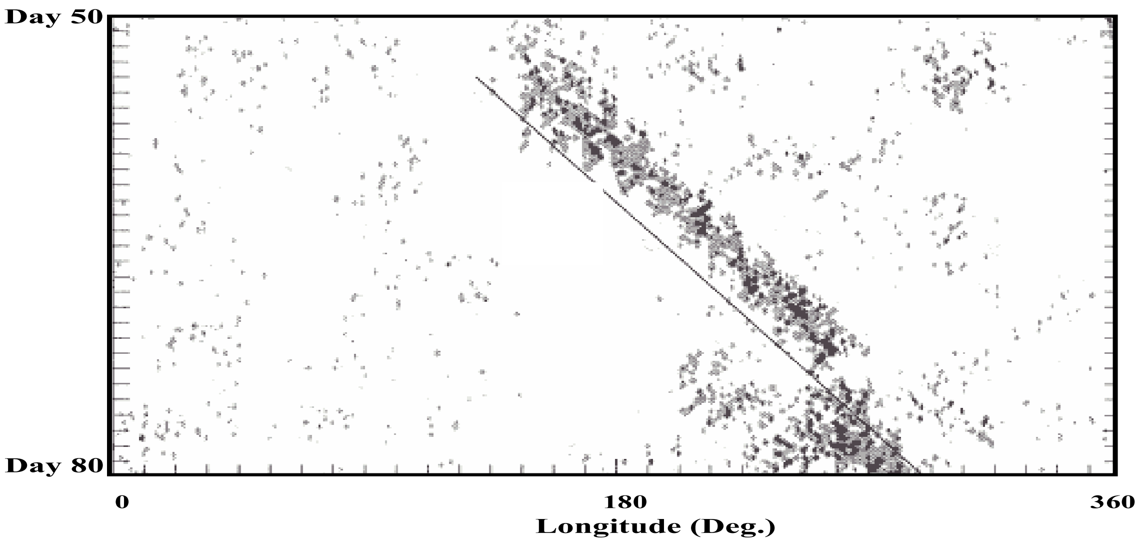

Fig. 2.6: MJO-like convective precipitation system at 5.6N from an idealized aqua-planet simulation. Convection (grey shaded) is represented by "super-parameterisation" in the mesoscale-resolving model. Super-parameterisation involves inserting a 2-dimensional cloud model within each grid box of a courser resolution simulation. The MJO convective system evolved after ~50 days of integration starting from a randomly perturbed uniform state (from Grabowski 2001).

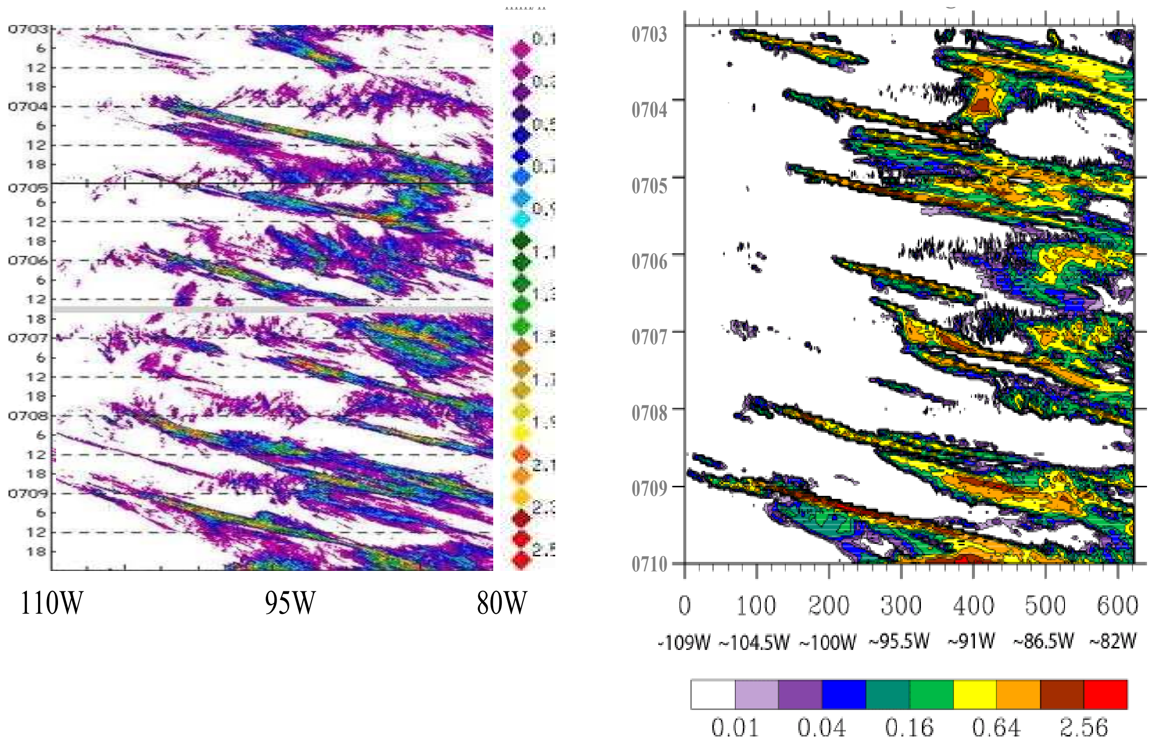

Fig. 2.7: Latitudinally averaged (30-48 N) rainfall rate for 3-10 July 2003 derived from (left) Stage IV radar observations and (right) a medium range WRF-model simulation that utilizes a 4-km horizontal grid spacing and explict deep convection , i.e, without cumulus parameterization (courtesy of Stan Trier NCAR/ MMM).

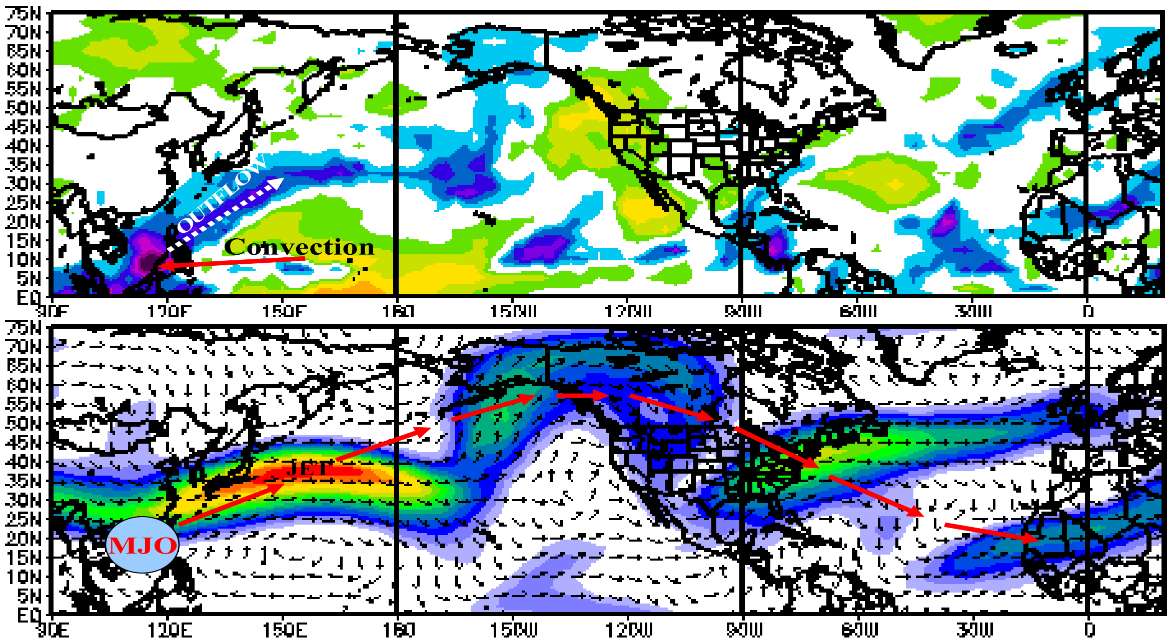

Fig. 2.8: Seven-day time-mean (18-24 December 1999) representation of a MJO tropical convective flare up and down-stream Rossby wave train for the period preceding the 24-26 December 1999 development of the ~100 ms^{-1} North Atlantic upper-level jet stream associated with the European extratropical cyclone "Lothar" and its destructive wind storm (see also Figs. 1.2 and 2.8). *Upper panel:* satellite-derived outgoing long-wave radiation, where blue into purple colour shading denotes radiation from cold cloud tops. The MJO tropical convective flare-up is centred over Indonesia (red arrow), with an out flow cloud plume extending north-eastward into mid latitudes (white dashed arrow). *Lower panel:* 250-mb wind velocity; direction, black arrows and speed, colour shaded; light blue, 20 ms^{-1}; red > 90 ms^{-1}. Centroid of MJO convection (blue circle); ray path of the Rossby wave train (red arrows).

2.3 Predictability Research

Uncertainty in numerical weather prediction

The factors that contribute to uncertainty in numerical weather prediction are: i) *uncertainty in the physical laws* governing atmospheric motions, notably in the numerical approximations used for their solution and the parameterizations of the unresolved (sub-grid) motions; ii) *uncertainty in the forecast initial conditions* arising from systematic and random errors in the observations, inhomogeneity in the spatial and temporal coverage of observations, representiveness of a given observing system to the spatial/temporal scales resolved by the forecast model, and approximations in data assimilation systems (Thompson 1957), referred to as *model uncertainty* and *initial condition uncertainty,* respectively. It is believed that the largest contribution to short-range forecast error is associated with initial-condition uncertainty. As the lead time of the forecast extends, model uncertainty becomes the more dominant factor in limiting predictive skill; Lorenz 1990. It is important to note that a forecast system with zero uncertainty in the forecast model or initial conditions will possess residual uncertainty, here referred to as the *intrinsic uncertainty*, produced by the unresolved motions that are independent of the motions resolved by the forecast model. This intrinsic uncertainty results from finite model resolution dictated by limitations in computational resources. THORPEX will address the relationship between model uncertainty, initial-condition uncertainty and the construction of ensemble-prediction systems, with the aspiration of producing forecasts with skill limited only by the intrinsic uncertainty.

Ensemble weather-prediction

Developments in numerical weather prediction have led to current forecast systems that use an *Ensemble Prediction System* (EPS) to assess the probability of occurrence of possible forecast outcomes (Palmer 2000 and references therein). An EPS is a collection of individual forecasts (*forecast members*) made from slightly different initial conditions and/or model formulations. The *spread* of the forecast member outcomes, defined as the *standard deviation* of the members from the *ensemble mean*, gives an estimate of EPS uncertainty. Estimates of the forecast uncertainty, for any forecast variable at any geographical location, are described by the *probability density function* (PDF) produced by a frequency distribution based on the various ensemble members. Figure 2.9 shows the ECMWF EPS members for the forecast of “Lothar”, the destructive French/German wind storm (Fig. 1.2).

Ensemble weather prediction can be described as a process leading to the computation of the *conditional probability distribution*; i.e., the PDF obtained from a forecast system conditional upon using a specific forecast model and its initial conditions, and thereby on the observations and the data assimilation system. At the start of the forecast, the PDF is initially narrow, with the initial spread of the ensemble members reflecting the likely uncertainty in the analysis. As the forecast lead-time increases, the chaotic growth of initially small perturbations leads to forecasts becoming increasingly uncertain and predictability for the small scales is lost within a relatively short time, with a subsequent loss of predictability for the larger spatial scales. A skilful EPS aims to capture the evolution of this PDF. Hence, the PDF will vary with location and time, so that, for example, day-two forecast uncertainty is likely to be larger for a developing cyclone than for a quasi-static anticyclone. For an EPS to be skilful, the PDF must possess two properties: i) it must encompass the weather that actually occurs, i.e., the verifying observations, and ii) at forecast lead times shorter than the predictability limit, it must be either narrower or with a different mean (or both) than the climatological probability distribution appropriate to the particular meteorological situation (Fig. 2.10). If the forecast PDF possesses the above properties, then the forecast is more skilful than the appropriate climatology.

Further improvement in EPS skill will be derived from research leading to forecast systems in which: i) the forecast PDF is as narrow as possible; ii) its ensemble-mean is, on average, as close as possible to the verifying analysis. As noted above, the intrinsic uncertainty produced by the unresolved motions, that are independent of the motions resolved by the forecast model, results from finite model resolution dictated by limitations in computational resources. The forecast PDF implied by this intrinsic uncertainty defines what is sometimes called the potential predictability of the system. The difference between the actual forecast and that associated with the potential predictability defines the scope for improving the forecast skill by reducing the above uncertainties and increasing computational power. THORPEX will carry out research to reduce this difference. An approach to incorporating intrinsic uncertainty is to develop parameterizations that are stochastic, i.e., time tendencies in the models that include a random component.

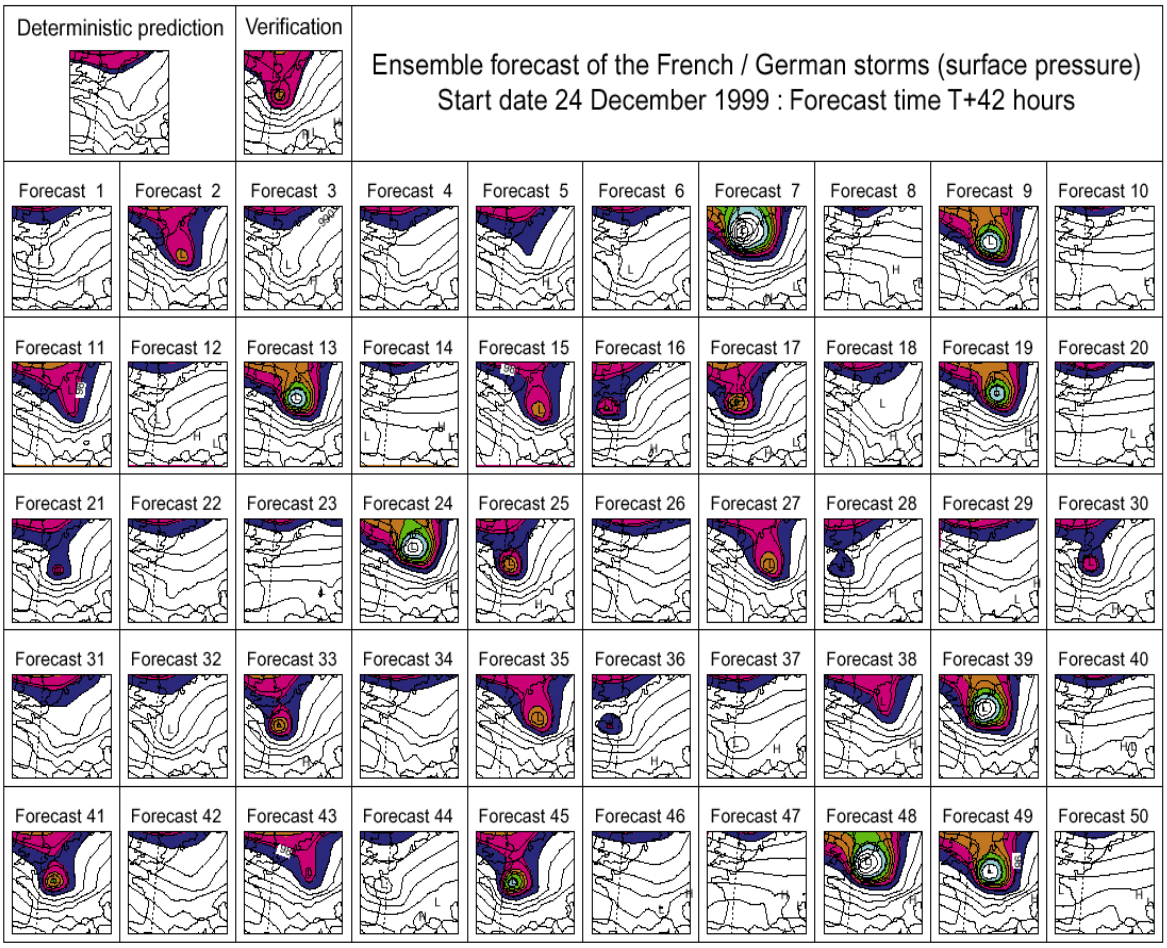

Fig 2.9: 42-h Ensemble forecast for the destructive French/German wind storm "Lothar" (Fig. 1.1) from the European Centre for Medium-range Weather Forecasts (ECMWF), TL255 rerun of the operational EPS, verifying a 1200 UTC 26 December 1999. Mean seal-level pressure (lines and shaded; 4-mb interval). *Upper 2 panels:* deterministic prediction (left) and verification analysis (right). *Lower 50 panels*: individual ensemble members. Note that though the deterministic forecast does not capture this extreme event, 14 of the ensemble members predict a storm of equal or greater intensity than the verification analysis (courtesy of Federico Grazzini ECMWF).

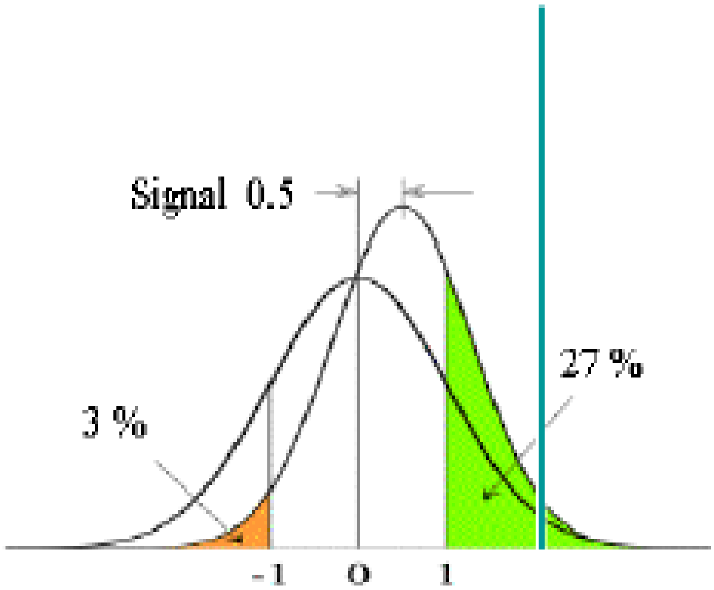

Fig. 2.10: Schematic probability density functions illustrating the climatology (with zero mean), and the forecast PDF (displaced from zero mean) at some forecast lead time, evolved from an initially narrow PDF (blue vertical line). For the EPS to be reliable, the verifying analysis at that lead time must fall within the climatology. The coloured areas indicate the chances of the verifying analysis falling at the extremes of the climatology, which are substantially different from the 16% chance expected from climatology.

In order to fully assess the potential societal/economic impact of predicted weather, it may be advantageous to perform higher resolution re-forecasts of the subset of global ensemble members that contain the highest risk. This is dynamical downscaling on a global scale to resolve high-impact weather with the finest EPS resolution possible, given operational computational constraints. In addition, global ensemble forecasts can be used to provide a measure of lateral boundary condition uncertainty for regional high-resolution ensemble forecasts. The boundary-condition uncertainty can be taken from the full suite of global EPS membership or from the subset of members displaying the highest potential for high-impact weather within a given regional domain. Depending on the lead-time of the regional forecast, this source of boundary-condition uncertainty can arise from anywhere on the globe.

In summary, EPS members should encompass the range of uncertainty in the forecast model, the data assimilation algorithm and the initial conditions. Current operational EPSs do not fully address all sources of forecast uncertainty because: i) the ensemble initial conditions do not adequately sample the distribution of possible analysis states; ii) the effect of un-parameterized unresolved variability on the resolved scales is neglected or misrepresented; iii) model uncertainties, especially those associated with parameterizations, are not properly accounted for. Research is underway to address these issues, but most current operational efforts have been devoted to initializing ensembles using initial conditions within a range of uncertainty arising from instrumental error characteristics and observational representivity error. Operational centers, such as the Meteorological Service of Canada (MSC) and the European Centre for Medium-range Weather Forecasts (ECMWF), have recently incorporated model-uncertainty into their ensemble forecast systems (e.g., Barkmeijer *et al.* 2003). THORPEX is dedicated to improving estimates of the forecast PDF through research on all sources of forecast uncertainty. THORPEX will explore the potential of a multi-analysis multi-model EPS constructed by utilizing the existing ensemble forecasts from various national forecast centres.

Weather prediction on sub-seasonal time scales

Forecast skill, as determined by the time at which the 500-mb anomaly correlation skill score falls below 60%, has advanced from ~5 days in 1980 to ~8 days in 2003. Useful weather forecasts into the second week have been possible since the year 2000. Further improvements in forecast systems will be required to achieve comparable skill out to14 days and beyond. Recent research using simplified models suggests that there is potential skill in forecasting weekly averages several weeks ahead. For example, using inverse models (e.g., Winkler et al 2001), weekly averages of extratropical weather were shown to be predictable only about two weeks ahead if the influence of tropical heating is ignored, but might be predictable as far as six weeks ahead, in some locations, if that influence were properly taken into account. These results were obtained from a simplified linear, stochastically-forced inverse model of the extratropical circulation and tropical heating variations derived from their observed simultaneous and lag-correlation statistics. Such models have been shown to be competitive with current operational forecast models at 2-3 week sub-seasonal forecast ranges. This strongly suggests that weather forecast prediction systems with improved resolution of tropical convection and heating may exhibit longer-range predictive skill than currently possible. Predicting the initiation and evolution of tropical convection (Section 2.2) requires: i) very high model resolution to explicitly resolve convection, or alternatively, improved convective parameterization; ii) a coupled atmosphere-ocean prediction system; iii) improved representations of atmospheric and oceanic boundary layers. For sub-seasonal predictions at 2-weeks and beyond, it may be necessary for the ocean component of the forecast system to be extended from a simple one-dimensional mixed-layer description to the inclusion of the three-dimensional evolution of the ocean state.

Improving the skill of sub-seasonal weather forecasts: the intersection of weather and climate prediction

The computational resolution of current *centennial* time-scale climate change prediction models (~T100L50) provides a course-grain representation of the meridional heat and momentum fluxes by the synoptic-scale eddies, but precludes the accurate representation of the sub-synoptic structures and physical process that are critical components in the development of hazardous weather. For this reason, the climatological statistics of hazardous weather events within global warming scenarios, e.g., i) rapidly developing extratropical cyclones; ii) category 3-5 tropical cyclones; iii) storm surges; iv) topographically induced floods, are not skilfully accounted for. Recent advances in computer technology have led to *seasonal* time-scale simulations, with a resolution of ~T1000L100 (~10-km horizontal, ~500-m vertical) exceeding that of today's operational medium-range global forecast models. These high-resolution short-range climate simulations, such as the example shown in Fig. 2.11, develop realistic representations of: i) equatorial moist convection; ii) tropical and extratropical cyclone life cycles, including many details of their sub-synoptic-scale structure and physical processes, such as, fronts and their associated mesoscale precipitation systems; iii) tropical cyclones with well defined convective eye walls; iv) polar lows. It remains to be shown whether the climatology of hazardous weather events within these simulations is representative of that of the atmosphere.

As noted above, uncertainty in the physical-process parameterizations of sub-grid-scale motions in present-day global weather forecast and climate prediction models contribute to limits in the skill of week-2 of weather forecast systems, and seasonal and inter-annual climate predictions. It will soon be feasible to carry out experimental 1-30 day global simulations of the Earth System with ultra-high-resolution coupled atmosphere/ocean models (~1-km horizontal by 100-meter vertical resolution for the atmosphere; 10-km by 50 levels for the ocean) that explicitly resolve, e.g.: i) convective cloud systems and ii) inertia-gravity waves, as is the case for today's high-resolution regional-prediction systems (Fig. 2.12, 2.13, and 2.14). These high-resolution global models would serve as prototypes for the development of the next generation of global weather forecast and climate prediction systems, anticipating the computational capacity of future computers. In the interim, these prototypes can be used as test beds: i) to improve parameterizations in the current global forecast and climate models; ii) for academic research to advance the science; iii) to provide the "nature" runs for testing advanced data assimilation systems and assessing requirements for next generation observing systems. Progress in the development of a unified global weather/climate prediction system to improve forecast skill on time ranges from days to centuries would benefit from collaboration between THORPEX, the World Climate Research Programme, and the mesoscale/microscale community.

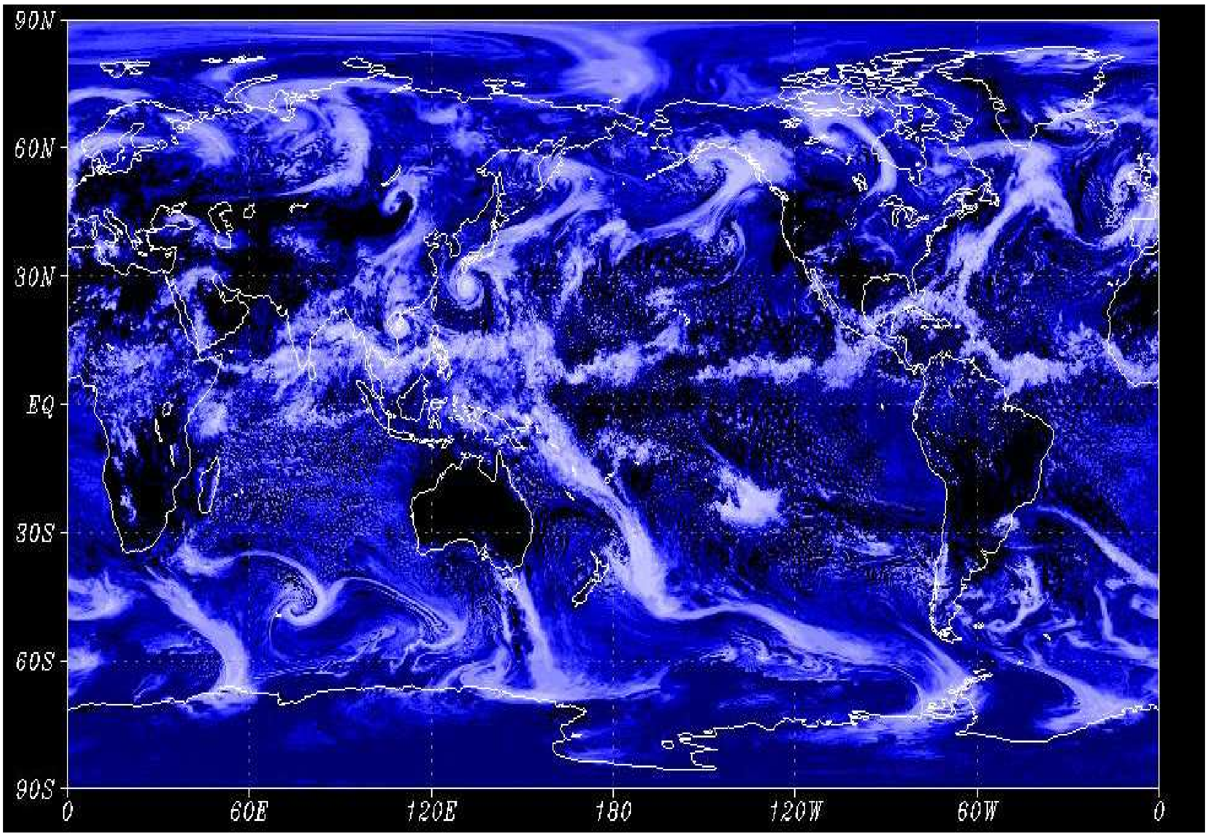

Fig. 1.11: Earth Simulator high-resolution (T1279L96; ~10-km horizontal; ~ 500-m vertical) climate simulation of precipitation rate (0.0-30 mm h^{-1}, shaded blue through white). Initial conditions are for early September using a climatological SST run for 12 years at T319L24 resolution (from Ohfuchi, *et al.* 2004).

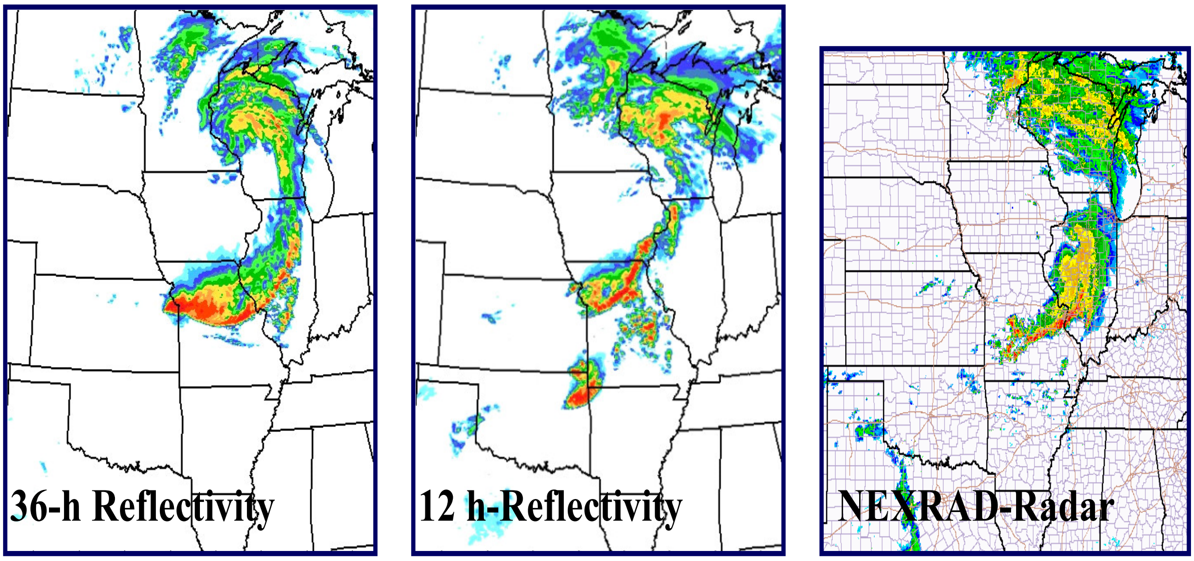

Fig. 2.12: Weather Research and Forecasting (WRF) prediction of organised mesoscale convection over the central U.S verifying at 1200 UTC 10 June, 2003. The WRF Mass Coordinate model was integrated on a 4-km resolution grid using explicit resolution of cumulus convection. *Left panel*: 36-h forecast reflectivity; *middle pane :* 12-h WRF forecast; *right panel*: observed radar reflectivity (courtesy Chris Davis NCAR/MMM).

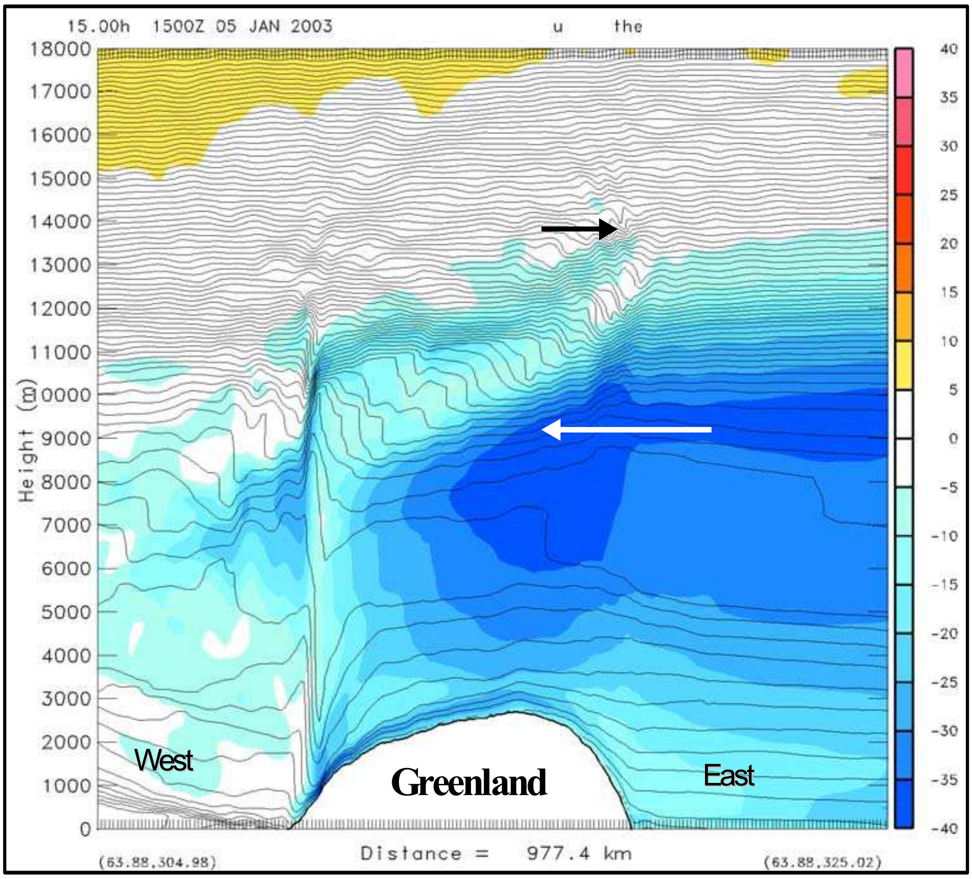

Fig. 2.13: Numerical simulation of breaking gravity waves at 1500 UTC 5 January 2003 (15-h simulation time) generated by easterly flow over southern Greenland. The simulation is from the non-hydrostatic Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) with a resolution of 5-km; 60 vertical levels for the third inner-most mesh The vertical cross section is oriented east-west across southern Greenland; u-wind component (color scale every 5 ms^{-1}) and potential temperature (solid lines at 2 K intervals), courtesy of Jim Doyle (NRL/Monterey).

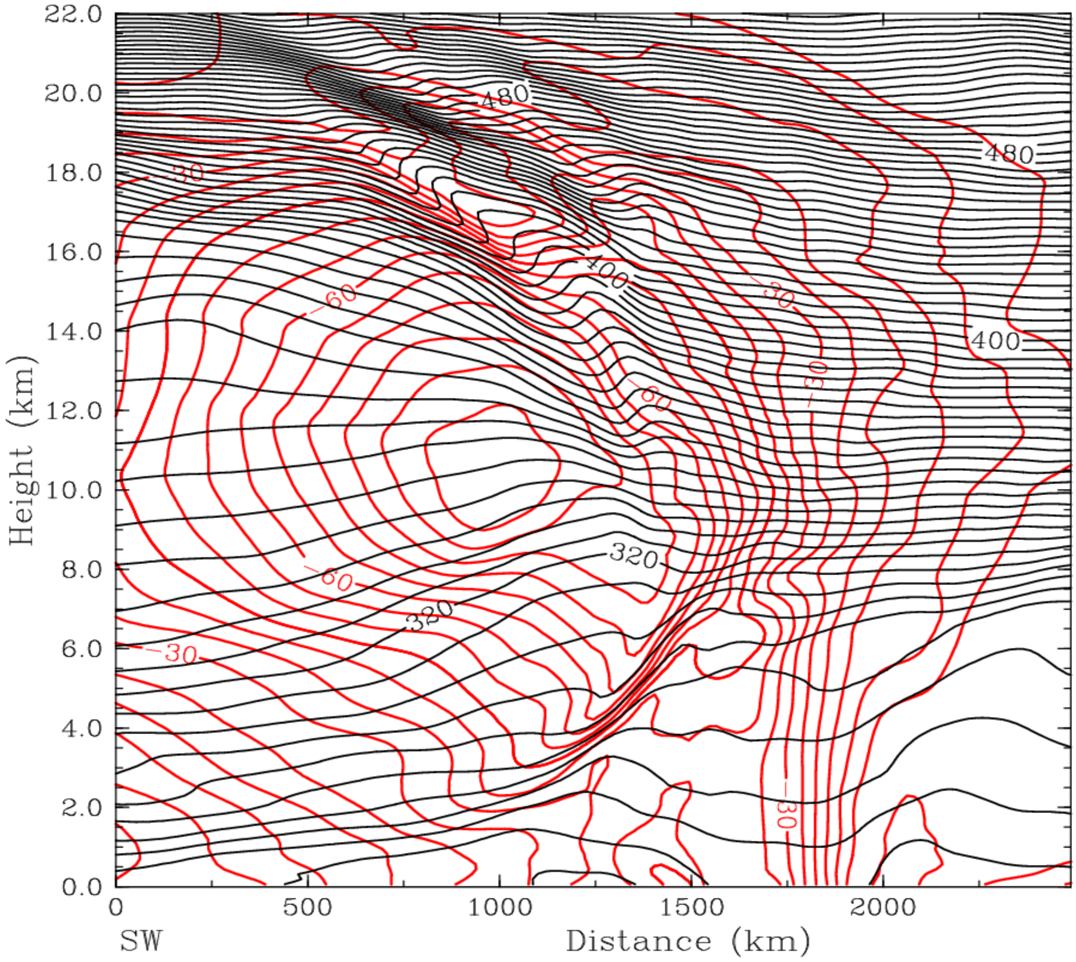

Fig. 2.14: A numerical simulation of an upper-level jet-stream/frontal-zone system and associated inertia-gravity wave breaking, north of Hawaii 2200 UTC 29 January 1998. The 12-h simulation is from the NCAR/Penn State MM-5 model, triply interactive and nested (27-9-3-km by 157-levels; 9-km shown above) within the ECMWF forecast. Note the vertically propagating and breaking inertia-gravity waves above the subtropical jet stream in the layer 12-22 km. Potential temperature (black lines at 4 K intervals; section-normal wind component (red lines, 5 m s^{-1} intervals). Courtesy of Andreas Dörnbrack (DLR).

2.4 Research Objectives

THORPEX predictability and dynamical processes research objectives:

Investigate the evolution of dynamical and physical processes and their influence on forecast skill: This objective will address dynamical and physical processes operating on various scales and their contribution to errors in high-impact forecasts. Studies of Rossby wave excitation and subsequent dispersion will address: i) the skill of forecast systems in predicting Rossby wave amplitudes, ray paths and group velocities; ii) the initiation of Rossby wave trains by organized tropical convection, extratropical cyclones and large-scale topography; iii) the initiation of tropical convection by Rossby wave-trains propagating from extratropics into the tropics. Coherent structures, such as discrete anomalies of PV, and the extratropical transition of tropical cyclones, will be investigated. Assessments will be made of global teleconnections, e.g., tropical-extratropical interaction, including the factors involved in their initiation and predictability.

Determine the influence of flow regimes on the climatology of forecast skill: This effort will assess sub-seasonal and inter-annual variability of forecast error, ensemble spread and the distribution of observationally sensitive regions. It will include determining the dependence of this variability on flow regimes, such as: i) zonal or blocked states; ii) phases, and sub-seasonal variability of prominent phenomena and major teleconnections, e.g., MJO, PNA, ENSO, NAO, and AO. The skill of EPS forecasts is modulated by temporal/spatial variations in meteorological regimes. For example, the skill in predicting extratropical cyclones over the eastern Pacific Ocean differs depending on the phase of ENSO (e.g., Shapiro et al. 2000). This is referred to as *regime-dependent evaluation* of forecast skill. THORPEX aims to fully explore this regime dependence, as this will provide substantial input to improved EPS design.

Assess predictive skill at all forecast ranges, including potential predictability: Key questions remain concerning the limits of predictability and what determines these limits. THORPEX aims to address these issues, including an assessment of the various limits of predictability appropriate to defined forecast attributes, and through this assessment explore new forecasting strategies to reduce these limits. Improved methods of generating ensembles will be used to investigate potential predictability, under the perfect model assumption, utilizing state-of-the-art operational forecast models to assess the potential for further improvements in predictive skill.

Quantify the contributions of initial condition and model uncertainty to forecast errors: The development of forecast systems depends critically on accurate estimates of the sources of forecast error attributable to initial condition uncertainty and forecast-model uncertainty. Research will quantify the influence of all sources of forecast error and their associated mechanisms for growth on different space and time scales and for different variables and different meteorological phenomena. This includes the uncertainty associated with numerical schemes, and uncertainty in parametrized and explicit physical processes, e.g., moist convection, boundary-layer exchange between the Earth's surface and free atmosphere, inertia-gravity-wave breaking and associated turbulence (over steep topography and in the vicinity of tropopause-based jet streams). Improved estimates of the relative contribution of the various sources of forecast error growth will lead to improved probabilistic forecasts and user products.

Investigate the relative effects of small and large-scale initial-condition uncertainty: Forecast errors can grow rapidly upscale from initial uncertainties in the small-scale motions. However, analysis and forecast uncertainties are dominated by the slower growing, and more energetic, larger-scale motions. THORPEX will address the relative roles of these two sources of initial uncertainty in limiting forecast skill. This will provide guidance for the design of improved observation systems and observing strategies by addressing questions such as whether observations should be targeted in localized regions of rapid forecast error growth, or whether it is preferable to reduce initial uncertainty at the larger scales by distributing observations over broader areas.

Develop improved global ensemble-prediction systems: Ensemble perturbations represent uncertainty in all aspects of the forecast initial state, including uncertainty in land and ocean surface conditions. Advanced methods must be developed to better account for: i) uncertainties in the effect of un-parameterized, unresolved phenomena on the resolved scales; ii) uncertainties in forecast model formulation, e.g., numerical approximations and process parameterizations. This research will include investigations of multi-model and multi-parameter ensemble prediction methods, as well as stochastic parameterizations. Recent research shows that there is useful additional ensemble spread contributed by multi-model or multi-parameterization ensembles (Khrishnamurti *et al.* 1999). However, these techniques are mostly *ad-hoc*, and it is not established whether their benefit is from the diversity of forecast models or the differences in initial conditions provided by different data assimilation systems. THORPEX will develop, demonstrate and evaluate a multi-model, multi-analysis and multi-national ensemble prediction system, referred to as the *THORPEX Interactive Grand Global Ensemble* (TIGGE). The TIGGE will integrate user requirements for forecast information, developments in observing systems, targeting, adaptive data assimilation, and model improvements into a multi-model/multi-analysis ensemble prediction system. TIGGE data bases, containing individual model EPS analyses and forecasts will be required to facilitate research on the design of best configuration of multi-model/multi-analysis ensemble forecast systems. TIGGE prototype forecast systems, resulting from this research, will be used to produce experimental real-time forecasts. The skill of these experimental forecasts will be evaluated relative to existing techniques. These forecasts should be tailored according to the severity of the predicted weather hazards. An operational forecast system of this design would allow international resources to be brought to bear on the most critical environmental forecast problems of the day.

Utilise global ensemble prediction systems to specify boundary conditions for high-resolution regional ensemble forecasts: It is recognised that a major source of error in high-resolution regional forecasts arises from errors in the course-grain forecasts that provide the time-variant lateral boundary conditions on the regional domains. THORPEX will demonstrate and assess the utility of regional ensemble prediction systems with members perturbed by uncertainty in lateral boundary conditions imposed by single model and multi-model global ensemble forecasts.

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3. Observing Systems Research

3.1 Rationale

The past half-century has witnessed dramatic advances in our ability to observe the Earth System. Four decades ago, operational numerical weather prediction relied almost exclusively on *in-situ* surface and upper-air radiosonde measurements taken at synoptic times (i.e., 12-hourly frequency). These observations formed the database for initialising numerical forecast models, as well as providing long-term records for climate monitoring. Today, observations are provided by satellite-borne remote sensors, supplemented by surface and upper-air observations, e.g., radiosondes; commercial aircraft flight-level and ascent/descent soundings; targeted dropsondes deployed from weather reconnaissance aircraft; radar wind profilers; surface observations from land and sea (Fig. 3.1 and Table 1). As a result, most observations of the Earth System are now asynoptic (taken at any place or time), creating new opportunities for improving the initialisation of operational forecast systems. The future will maintain the relentless acceleration in the diversity, quality and volume of satellite observations, but with the potential for a new generation of *in-situ* sensing deployment systems designed specifically to complement and enhance the utility of satellite observations. THORPEX will contribute to the further development of a multi-sensor global observing system that meets the requirements for accelerating improvements of high-impact weather forecasts, short-term weather warnings, and climate monitoring. This research will include accounting for the methods used to assimilate the observations. Data assimilation systems provide valuable information on the requirements of observing systems (spatial/ temporal resolution; accuracy; representivity, etc.) and their relative contribution to the skill of forecasts.

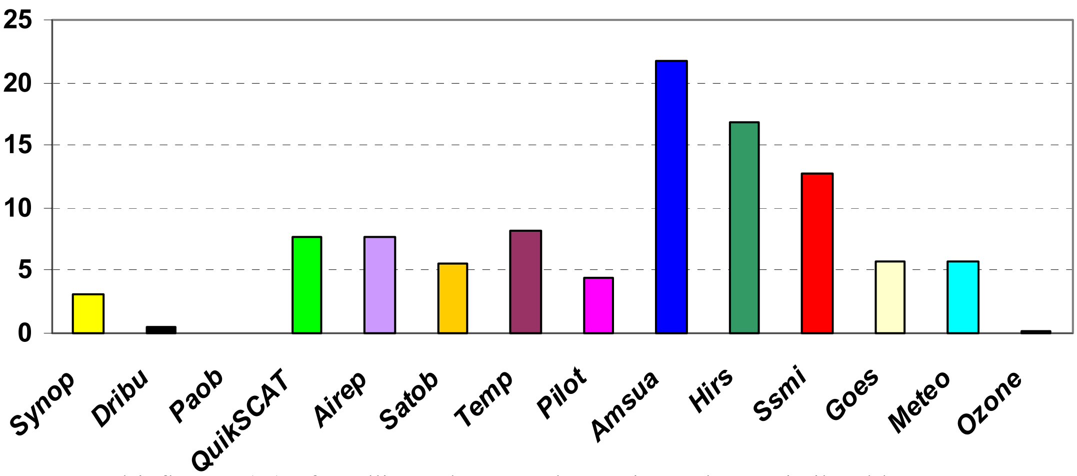

Fig. 3.1: Total influence (%) of satellite and *in-situ* observations when assimilated by ECMWF 4DVar System. **Synop:** surface obs; **Dribu:** drifting buoys; **Paob:** Southern Hemispheric bogus obs.; **QuikSCAT:** scatterometer sea-surface winds; **Airep**: com. aircraft reports; **Satob:** satellite Geo./MODIS winds; **Temp:** radiosondes, land/sea; **Pilot:** pilot balloons**; Amsua:** AMSU temp./r.h. soundings; **Hirs:** hyper-spectral satellite soundings; **Ssmi:** microwave soundings/surface wind; **Goes** and **Meteo:** IR soundings; **Ozone:** radiative characteristics. The total influence (per type), as calculated during the assimilation cycle, depends on the number of observations assimilated (See Table 1). Consequently, AMSUA radiances show the largest total influence. Low-influence data points usually occur in data-rich areas, while high-influence data points are in data-sparse areas or in dynamically active regions. Also, high background (prior model information) correlation diminishes the observation influence and amplifies the importance of the surrounding observations; From Cardinali *et al*. 2004.

Type of Data	Description	Number of observations
SYNOP	Surface Observations from land and ship stations: measuring p_s, T, RH, horizontal wind velocity	36 889
QuikSCAT	Satellite microwave scatterometer derived measurement of sea-surface wind	114 220
DRIBU	Drifting buoy measuring p_s, T, RH, wind	3 419
SATOB	Satellite cloud/vapour drift winds	102 090
TEMP	Radiosondes from land and ship measuring p_s, T, RH , wind	61 205
AMSUA	Satellite microwave sounder radiances	641 274
PILOT	Sondes and Wind Profiler wind	45 060
HIRS	Satellite infrared radiances	163 134
AIREP	Aircraft measurements of T, wind	119545
SSMI	Satellite microwave imager radiances	116 739
PAOB	Surface pressure	219
GOES	Geostationary satellite infrared-sounder radiances	35 302
OZONE	Satellite ozone retrievals	11 058
METEOSAT	Geostationary satellite infrared sounder radiances	39 623
Total		1 489 777

Table 1: Number of observations, per observing system, assimilated into a typical ECMWF analysis cycle (courtesy Carla Cardineli ECMWF).

THORPEX observing-system research will explore the potential for new observing technologies to provide observations that improve the skill of high-impact weather forecasts. This will include the development and/or utilisation of: i) innovative airborne and surface-based technologies for obtaining *in-situ* upper-air soundings and surface observations; ii) airborne prototypes of next-generation space-based remote-sensing systems; iii) advanced methods of data processing for newly deployed satellite-based observing systems. This effort will involve collaboration between observing-system and data-assimilation researchers on: i) the assimilation of new observations, to include data characterization; quality control; data thinning; ii) Observing-System Simulation Experiments (OSSEs) and Observing-System Experiments (OSEs) that contribute the requirement of establishing the potential impact of next-generation observing systems on forecast skill; iii) observational representativity uncertainty. Research responsibilities include coordinating observational logistics of THORPEX observing-systems tests and field campaigns. These efforts will contribute to the demonstration and evaluation of the impact of observing systems within interactive forecast systems.

The following Sub-sections present an overview of *Remote-Sensing and In-situ Observing Systems* (3.2), followed by discussions of *Observing-System Simulation Experiments* (3.3); *THORPEX Observing System Tests*, *THORPEX Regional Campaigns*, *THORPEX participation in global prediction campaigns* (3.4) and *Research Objectives* (3.5).

3.2 Remote-Sensing and *In-situ* Observing Systems

Satellite-based observing systems

Geostationary satellites, low-earth-orbiting polar and non sun-synchronous satellites provide passive and/or active observations of energy emitted and reflected by the atmosphere and Earth's surface at wavelengths spanning the ultra-violet, visible, infrared, and microwave bands of the electromagnetic spectrum. These observations are used to derive imagery, cloud and precipitation properties, land and ocean-surface geophysical/biological characteristics, atmospheric composition, winds, and vertical profiles of geophysical parameters. Some geostationary satellite operators are developing sensors with greatly improved spectral and temporal coverage for imaging, as well as hyper-spectral infrared sounding and lightning mapping capability.[4] The polar orbiting component of the operational environmental satellite system will evolve to include constellations of satellites in sun-synchronous orbits carrying high-resolution multi-spectral imagers, very high-spectral-resolution infrared sounders, advanced microwave imagers and sounders, improved ozone monitoring instruments, and radio occultation (GPS) sensors. The key characteristics of satellite-based observing systems are summarized as follows:

Infrared imagers and sounders**:** During the time frame of THORPEX, *infrared imagers* will evolve from observing within a few broad spectral bands into high-resolution advanced imagers with up to tens of narrow bands, and with a spatial resolution approaching 250 m. These enhancements will provide improved estimates of: cloud properties; aerosols; ocean properties, such as turbidity and sea surface temperature; land characteristics (e.g., snow cover, vegetation, and surface temperature); winds derived from tracking clouds and water vapour from geostationary satellites (Fig. 3.2). Successive and frequent images from polar-orbiting satellites currently provide wind-information pole ward of the field of view for geostationary satellites (Fig. 3.3).

The spectral resolution for selective infrared sounders will increase from sensing a limited number of broad spectral regions to over 2,500 very narrow spectral bands. When deployed, these advanced infrared sounders and imagers will multiply the number of satellite observations available to operational NWP by a factor of nearly 10^5. Hyper-spectral sounders on polar-orbiting and geostationary satellites will provide observations that resolve temperature and water vapour distributions with far greater vertical resolution than current sounders. These advanced sounders will lead to improved water-vapour-tracked wind observations through higher-resolution water-vapour profiles (Fig.3.4). In combination with observations from infrared imagers, advanced sounders will provide more accurate surface temperature measurements in cloud-free areas. Because infrared observations can be attenuated by the presence of dense cloud layers, current forecast systems utilize only cloud-free clear-column radiances. Furthermore, because of variable surface emissivity over land, forecast systems only use radiances that are not influenced by the surface. Improvements in both these areas will occur during the lifetime of THORPEX.

[4] Information on both research and operational meteorological satellite systems can be accessed through the WMO Space Programme Web Site (http://www.wmo.ch/hinsman/satopstatus.html).

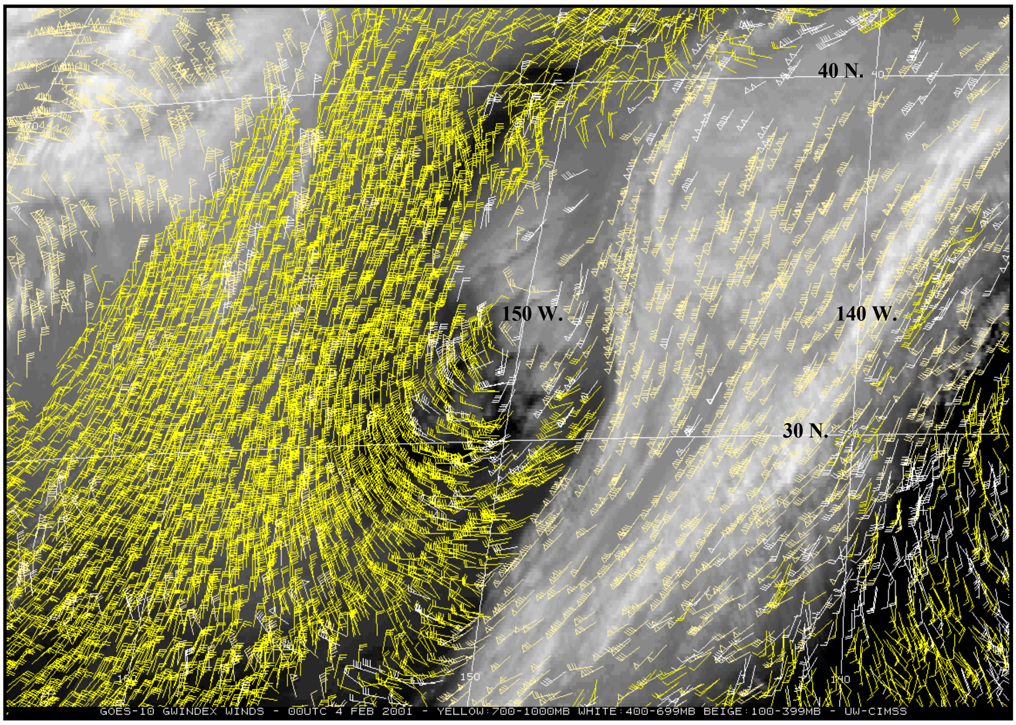

Fig. 3.2: Multi-spectral winds (knots) and water vapour image (shaded) at 0000 UTC 4 February 2001, derived from NOAA GOES-10 geostationary satellite visible, infrared and water vapour images. Yellow, cyan and white vectors indicate winds in layers at 1000-700, 699-400, and 399-100 hPa, respectively (courtesy of Chis Velden CIMMS/U. Wisc).

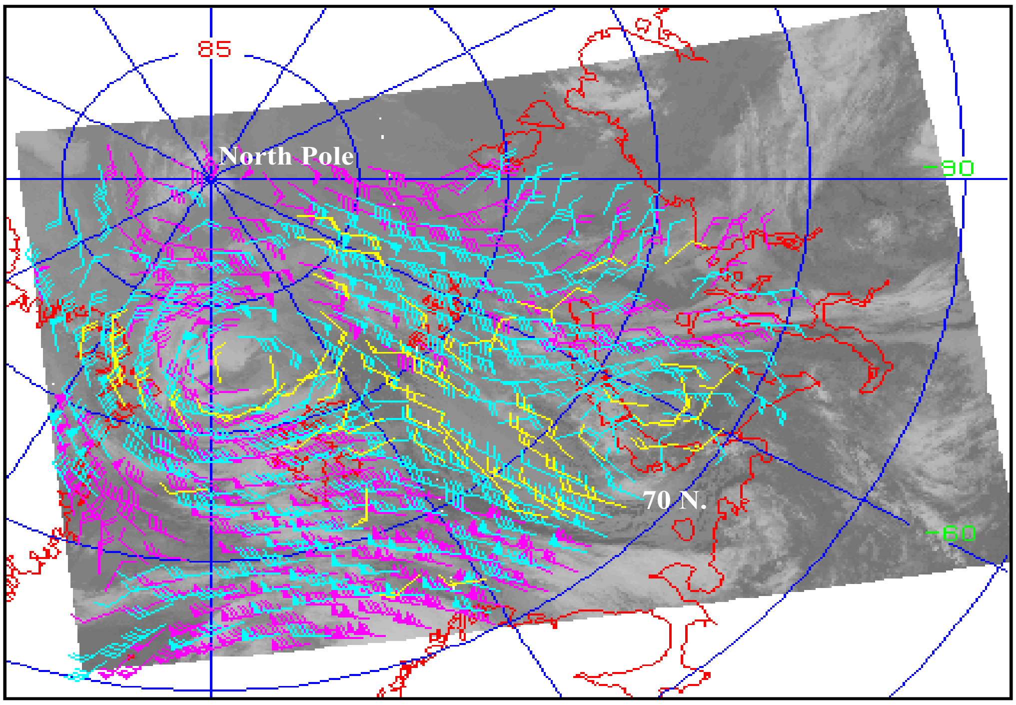

Fig. 3.3: MODIS multi-spectral winds (knots) over arctic latitudes at 1545 UTC 9 September 2004, derived from successive overpasses by polar-orbiting satellites. Colour-coded winds: above 400 mb, magenta; 700-400 mb, blue; below 700 mb, yellow (courtesy Chris Velden CIMMS/ U. Wisc.).

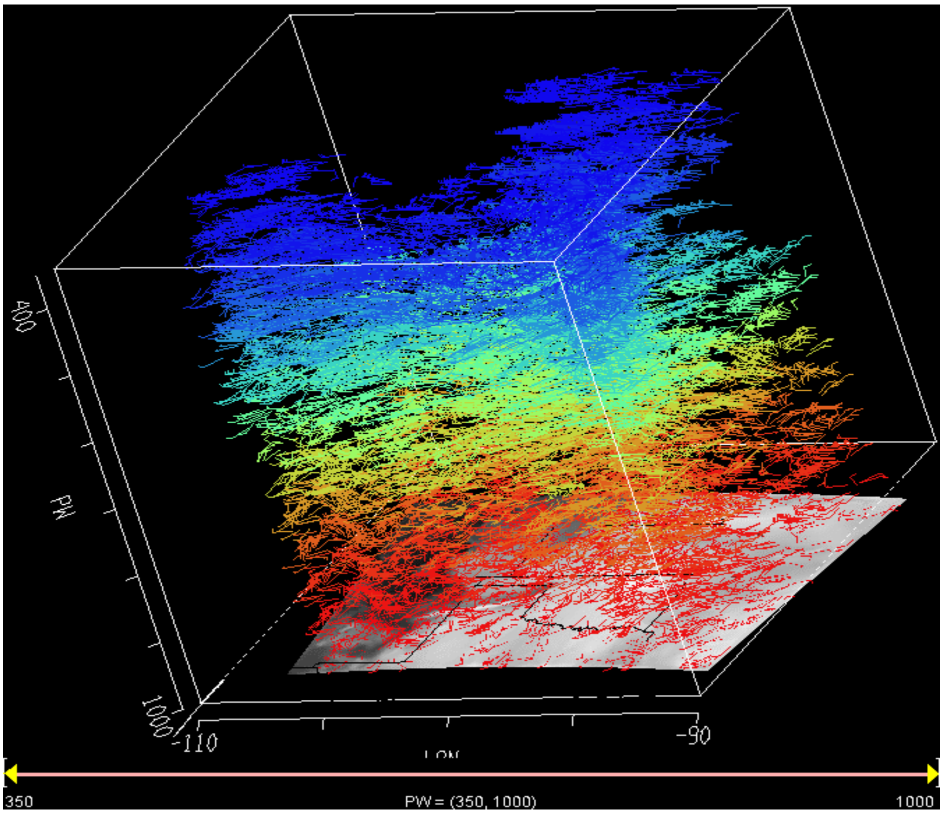

Fig. 3.4: Simulated hyper-spectral winds over the central U.S illustrating the horizontal density and vertical distribution winds from next-generation geostationary sounders. The potential high density of these measurements will likely require data thinning for assimilation into operational forecast systems (courtesy of Bill Smith, University of Wisconsin.).

Microwave sounders and imagers: The vertical resolution of microwave soundings is limited when compared to soundings derived from their infrared counterparts. In spite of this limitation, microwave sounders provide valuable thermodynamic profiles in regions opaque to infrared sensors (e.g., within and beneath those dense cloud layers which are often regions of dynamical importance and sources of forecast error growth). Microwave sensor observations are also used to derive: i) thermodynamic soundings with high-horizontal resolution in clear and cloudy and clear areas; ii) sea-surface winds; iii) cloud microphysical properties (Fig. 3.5); iv) precipitation intensity and amount. Next-generation microwave sensors will provide higher spatial resolution observations than those of the current generation, and will include additional spectral channels for imaging, soundings, and products, e.g., soil moisture; sea surface temperature; sea surface wind vector; precipitation; cloud properties; and land and sea ice.

Ultra-violet (UV) backscatter: The NASA Total Ozone Mapping Spectrometer (TOMS) measures total columnar ozone indirectly by mapping ultraviolet light emitted by the Sun in reference to that scattered from the Earth's atmosphere back to a polar-orbiting the satellite (Fig.3.6). The high-correlation between tropopause height, potential vorticity anomalies and lower-stratospheric ozone has led to experimental studies that assimilate the dynamical attributes of stratospheric ozone into numerical forecast systems, e.g., Zou, *et al.* 2003. Geostationary deployments of TOMS sensors have the potential to provide high horizontal/temporal resolution ozone input into advanced data assimilation systems, including stratospheric ozone-drift winds.

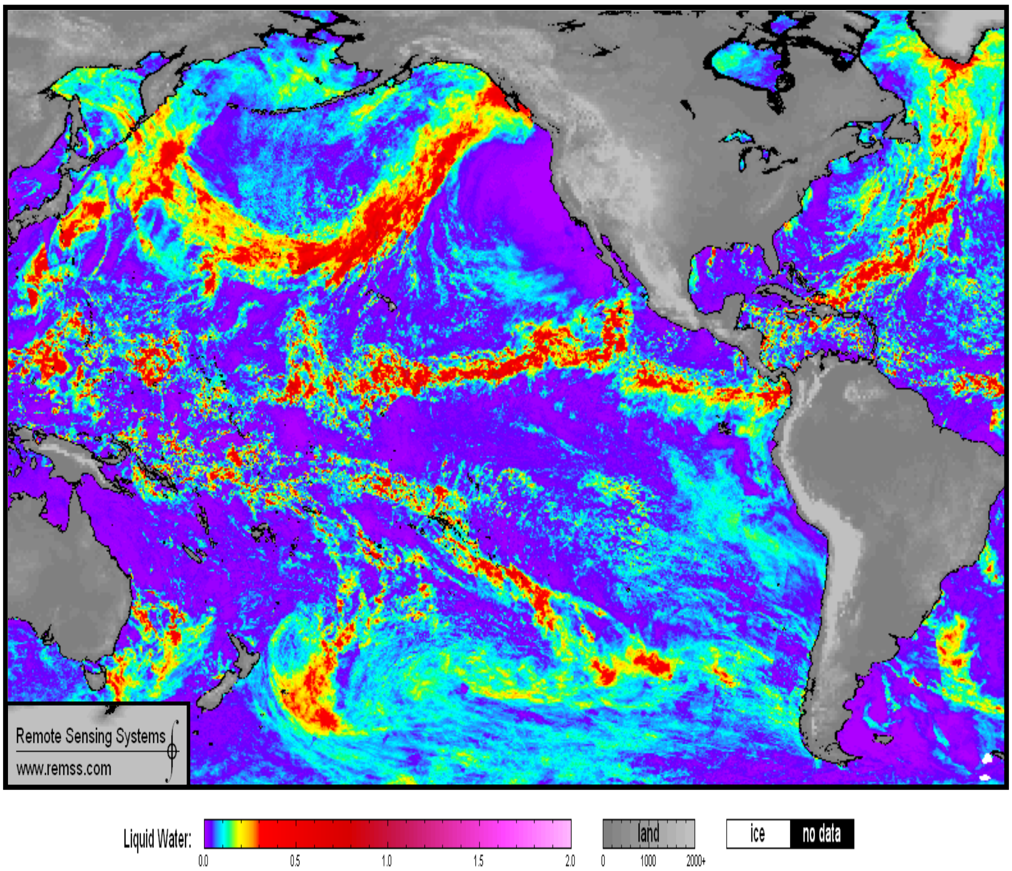

Fig. 3.5: ARMS cloud liquid water for 3 days ending 26 October 2003.

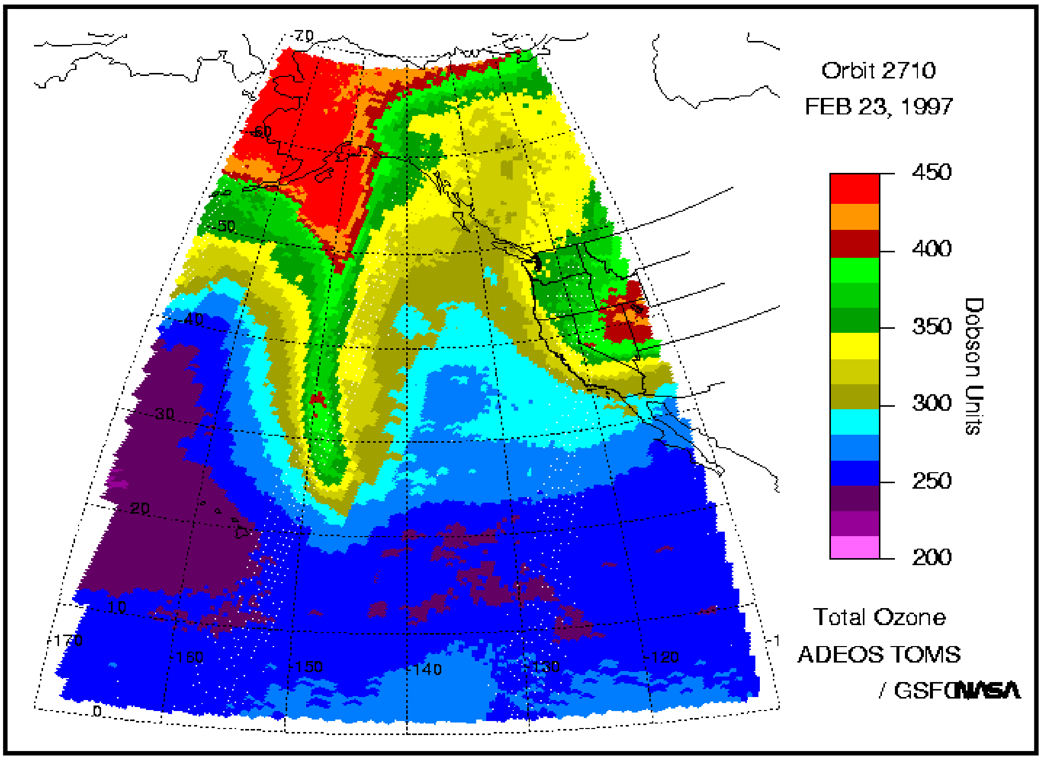

Fig. 3.6: UV-backscatter image of total columnar ozone (Dobson Units, colour bar) from the NASA Total Ozone Mapping Sectrometer (TOMS) on 23 February 1997.

Active remote sensing from satellites: The next generation of satellite active remote-sensing systems will provide high-spatial resolution measurements and derived profiles of precipitation, cloud, water vapour, ozone, aerosols, potentially other atmospheric constituents, and atmospheric motions. These observing systems include: i) microwave radars measuring reflectivity profiles of cloud, precipitation, and microphysical properties, and Doppler measurements of air motions within clouds and precipitation; ii) fixed beam and scanning Lidars that provide aerial images and vertical profiles of backscatter, differential-wavelength absorption, reflectivity, atmospheric composition (e.g., water vapour; ozone; aerosols), and winds. These observing technologies hold unexplored potential for numerical weather prediction applications by providing, e.g., i) highly-accurate height assignment for the assimilation of cloud-top infrared radiances; ii) improvements in the height assignment of multi-spectral winds derived from geostationary and polar orbiting satellites (See Figs. 3.7 and 3.8); iii) improvements in the characterization of model physics; iv) direct measurement of airflows. In addition, passive microwave sensing from a constellation of satellites can be combined with active dual-wavelength radar observations from a core satellite to improve both the frequency and accuracy of precipitation measurements from space. Space-based microwave scatterometers (e.g., QuikSCAT) provide global coverage for sea-surface winds (Fig. 3.9).

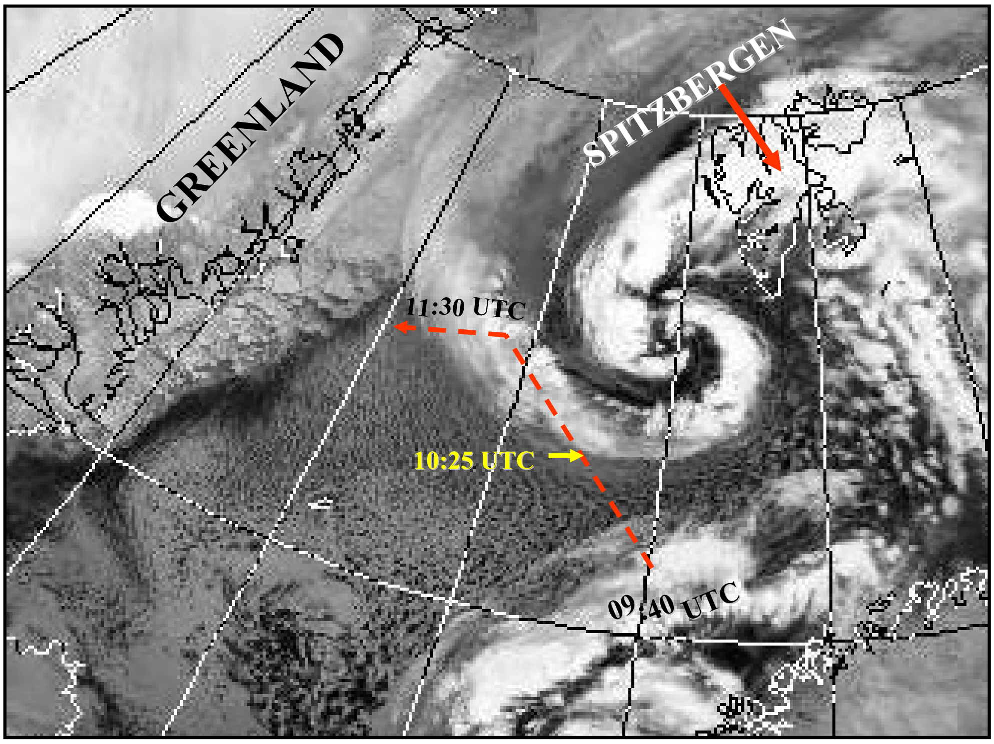

Fig. 3.7: 1240 UTC 16 December 1999 Dundee Satellite Receiving Station infrared satellite image of a polar low over the North Atlantic Ocean situated between Greenland and the southern tip of Spitzbergen. Red-dashed line delineates the flight track of the NASA DC-8 between 09:40 and 11:27 UTC along which the LASE water-vapour/and aerosol Lidar measurements of Fig. 3.8.

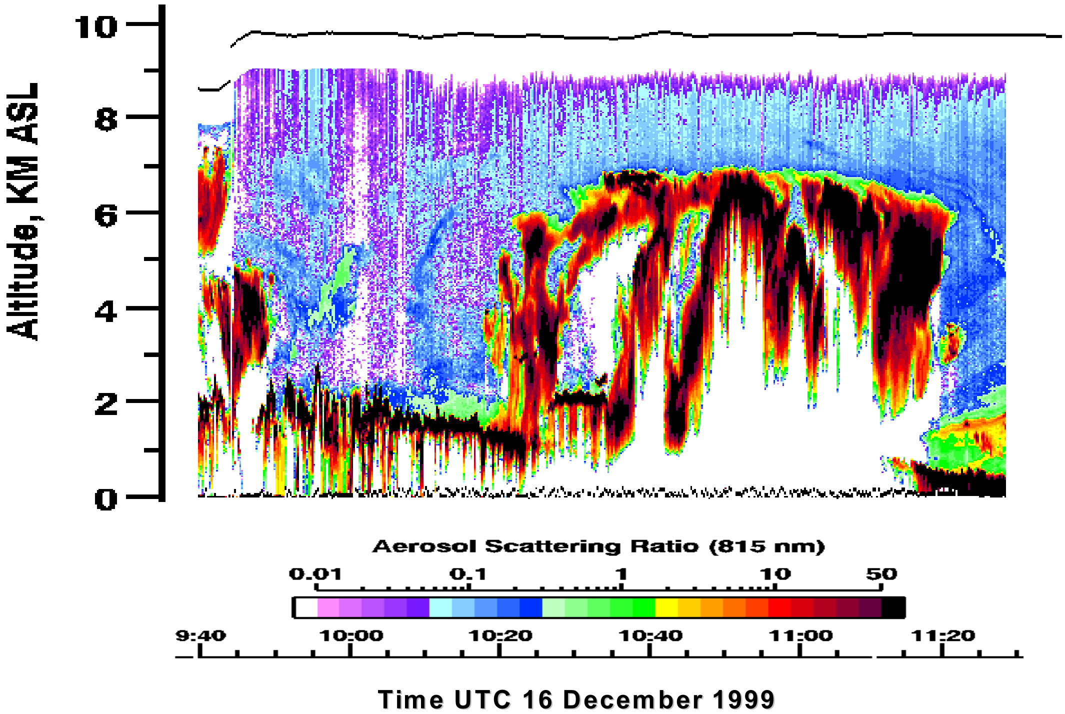

Fig: 3.8: SAGE-III Ozone Loss Validation Experiment-1 (SOLVE-1) LASE Flight 13 aerosol Lidar backscatter ratio observed along the line AB of Fig. 3.7. The sharp discontinuities in backscatter along the flight path occur at the cloud tops shown in Fig. 3.7. The discontinuity below 2 km between 09:50 and 10:25 UTC is at the top of the surface boundary where the shallow stratocumulus layer extends eastward in the arctic flow from off the East Greenland sea-ice shelf; ii) the discontinuity at ~6 km between 10:25 and 11:20 UTC is at the top of the cloud band that spirals inward to the polar low (courtesy of Edward Browell NASA Langley) .

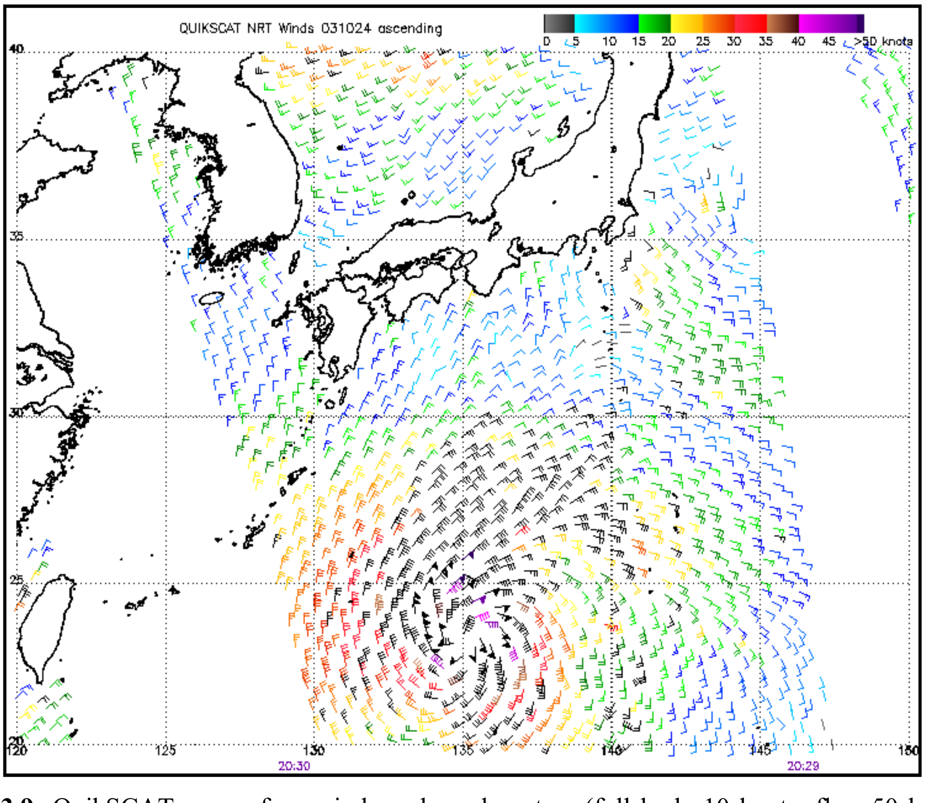

Fig. 3.9: QuikSCAT sea-surface winds, coloured vectors (full barb=10 knots; flag=50 knots) showing typhoon Parma southeast of Japan on 25 October 2003 (see Fig 3.10).

Combined active and passive microwave systems: The Tropical Rainfall Measuring Mission (TRMM) demonstrated the measurement of space-based estimates of rainfall rates over the ocean, including profiles of precipitation and observations of lightning. TRMM sensors include active radar and a dual polarized passive microwave sensor, as well as a high-resolution visible and infrared imager and a Lightning Imaging Sensor (LIS). Figure 3.10 presents the infrared cloud image with superimposed rainfall rate from TRMM for typhoon Parma on 25 October 2003, concurrent with the QUIKSCAT winds (Fig.3.9).

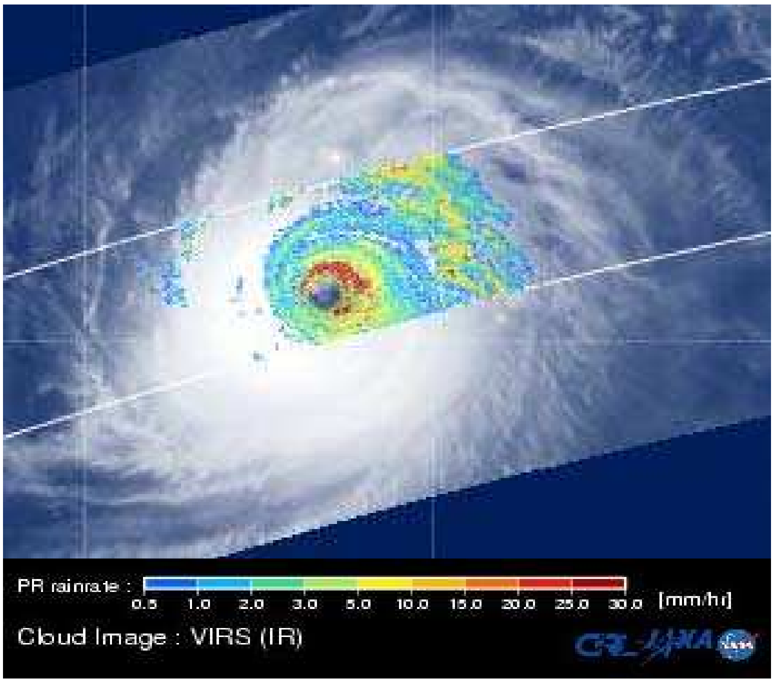

Fig. 3.10: TRMM rain rate (mm h^{-1}, colour bar) superimposed on Typhoon Parma VIRS IR cloud image on 25 October 2003 (See Fig. 3.9).

It is anticipated that the Global Precipitation Mission (GPM) will come to fruition within the THORPEX timeframe. The GPM concept includes a core satellite in a prograde orbit (inclination near 58 degrees) that carries enactive precipitation radar, as well as a passive microwave precipitation radiometer, accompanied by a constellation of sun-synchronous satellites with passive microwave precipitation radiometers. The core satellite will under fly the constellation of satellites and provide accurate calibration that will allow for the derivation of global precipitation at least eight times per day (more frequent in polar regions due to multiple area coverage from the sun-synchronous satellite observations). These global observations should prove invaluable as they become assimilated into forecast systems.

GPS Met: Radio-frequency signals from Global Positioning Satellites (GPS) can be used to obtain thermodynamic observations of the atmosphere. Surface-based receivers of GPS signals are used to derive vertically integrated water vapour and receiver-to-satellite measurements of atmospheric refractivity. Satellite-to-satellite signal transmission provides vertical profiles of atmospheric refractivity through active limb scanning, when signals from individual satellites within a constellation of GPS satellites undergo occultation by the atmosphere. The radio occultation technique provides: i) high-vertical resolution profiles of refractivity that are not severely affected by clouds or precipitation; ii) a global data set of electromagnetic energy travel time through various layers of the atmosphere that does not require calibration; iii) errors that are statistically independent of other types of satellite radiance measurements. The techniques are relatively new and constellations of satellites providing thousands of GPS occultation soundings daily are planned within the lifetime of the THORPEX programme (Fig. 3.11).

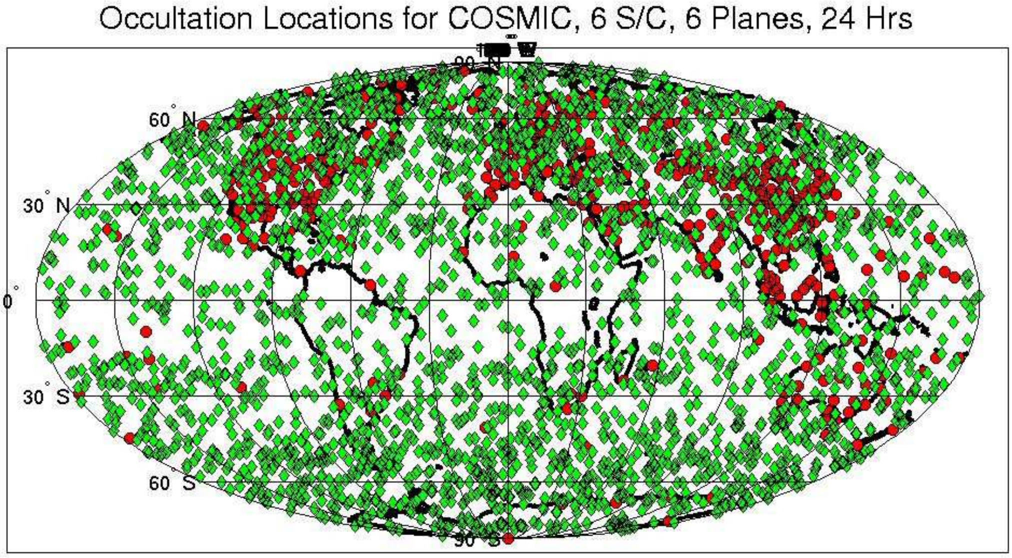

Fig. 3.11: Global distribution map of the number of GPS occultation soundings (green) to be provided by COSMIC satellites within a 24-h period and the current radiosonde network (red).

Surface-based remote sensing

Networks of surface-based remote sensing systems have been deployed to support hydrological applications, and mesoscale weather prediction and warning systems. Such networks are composed of: i) scanning conventional radars that measure the spatial distribution of reflectivity from large hydrometeors; ii) Doppler radars that measure reflectivity and spatial variations in the radial components of the wind velocity; iii) sodars and radar wind profilers that provide near-continuous time series of the vertical profile of wind velocity; iv) Radio Acoustic Sounding Systems (RASS) that measure vertical profiles of virtual temperature; v) high-spectral resolution interferometers that provide profiles of radiance in the lowest few km; vi) backscatter lidars from which boundary layer heights can be derived. Future networks may be deployed on ships, buoys and other ocean platforms. THORPEX will address the impact and importance of these networks to global prediction systems. For example, research could determine whether it is cost effective to obtain observations from wind profilers in remote regions (e.g., Arctic, central Australia, the African sub-Sahara) where manned *in-situ* observing sites are costly to maintain.

Advanced technologies for *in-situ* profiling systems and surface observations

THORPEX observing-systems research will contribute to the development and demonstration of advanced techniques for deploying *in-situ* profiling systems (e.g., radiosondes; dropsondes) and expanded surface observations. This effort stems from the requirement for improved coverage of *in-situ* observations in remote regions where: i) conventional radiosondes are difficult and/or costly to deploy, e.g., over oceans and polar regions; ii) satellite observing systems have reduced observing capabilities, such as within and below cloud layers opaque to infrared and visible sensing from space; iii) in polar latitudes, geostationary satellites provide limited observational coverage. These advanced deployment systems include:

***Surface deployments of upper-air sounding systems*:** Forecast improvements may result from targeting the timing of surface-based radiosonde launches as a supplement to, rather than relying solely on ascents at synpotic times. Observations may also be taken on both ascent and descent (bi-directional radiosondes), which may decrease the representivity errors. Another technical advance is the rocketsonde that deploys a GPS dropsonde from a surface-launched rocket reaches its maximum height of ~8 km. Rocketsondes could be deployed from ships, land, and sea-ice. In addition, the expansion of the Automated Shipboard Aerological Programme (ASAP) allows for radiosonde deployments from ocean-going merchant ships. ASAP and rocketsonde observations can be taken upon demand for targeted observing strategies. Finally, new sensors for conventional radiosondes may also allow more accurate measurements of water vapour in the upper troposphere.

***Stratospheric balloon and aircraft deployments of dropsondes*:** Technological advances in balloon materials, global communications, and *in-situ* profiling sensors have revived interest in stratospheric-balloon deployments of upper-air soundings. Current advances include the development of zero-pressure-difference balloons that carry a payload of ~20 dropsondes. Dropsonde carrier balloons, known as the driftsonde (Fig 3.12), travel for ~5 days at or above 100 mb and deploy dropsondes that provide high-vertical-resolution profiles of atmospheric temperature, pressure, humidity and wind, at scheduled times/locations or on-demand. Advances in dropsonde technology will soon allow dropsondes to be deployed from commercial aircraft and Unmanned Airborne Vehicles (UAVs). Dropsonde systems will soon be miniaturized to provide cost-effective deployments in large numbers to provide greater observational coverage of the Earth System.

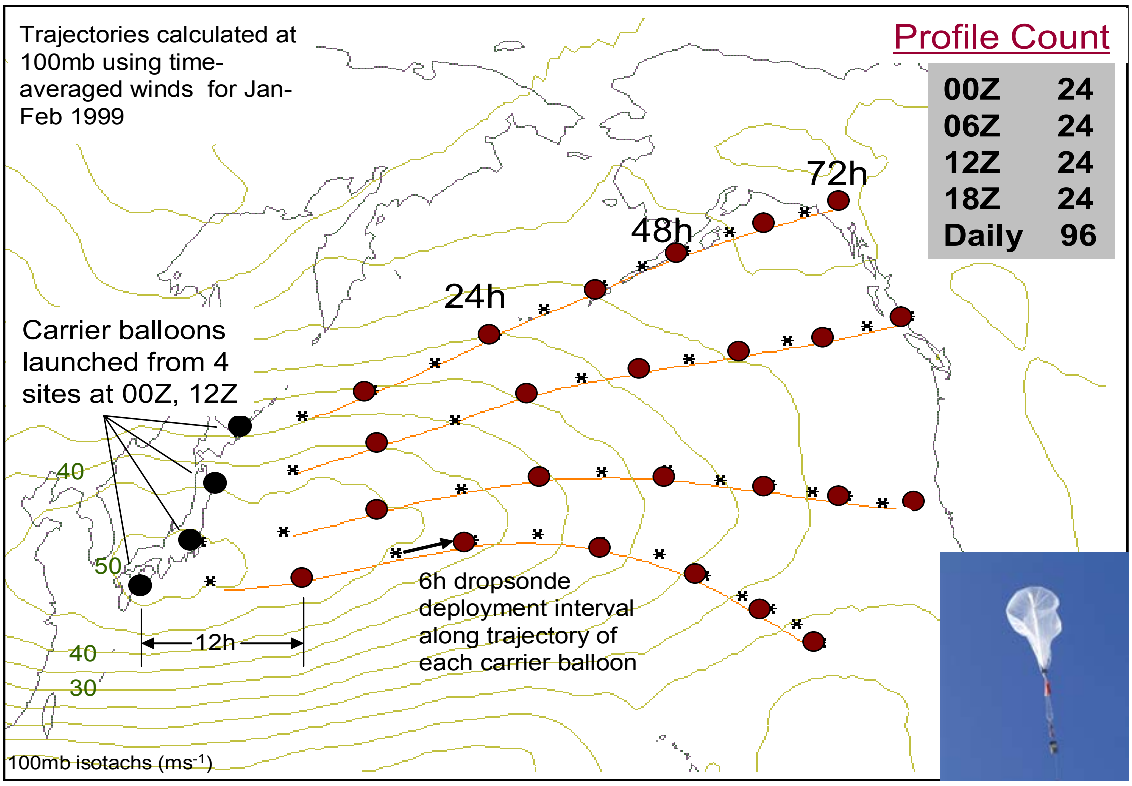

Fig. 3.12 Simulated Driftsonde profile coverage at one data-assimilation time, after 3 days of sonde deployment from 100 mb. The carrier balloons were launched from 4 sites in Japan (black dots). Each dot represents a separate carrier balloon / gondola and GPS dropsonde profile locations at 0000 or 1200 UTC (red dots). Stars are profile locations at 0600 or 1800 UTC. Insert photo (lower right) shows the full Driftsonde system test from Tillamook, Oregon on 28 February 2002 (courtesy of Rolf Langland NRL/Monterey).

***Aircraft flight-level observations*:** New technology has led to improvements in the quality and quantity of flight-level meteorological observations (from passenger and cargo aircraft during transit and ascent/descent). *In-situ* observing systems onboard regional-commuter/cargo, general-aviation and unmanned airborne vehicles (UAVs) provide additional vertical profiles, especially in areas distant from major continental and trans-continental airports and operational upper-air sites. *In-situ* observations can also be made from super-pressure balloons and "smart" balloons, steered by varying their altitude in the presence of vertical wind shear.

***Surface observations*:** The geographical coverage of surface *in-situ* observations has improved dramatically over the last decades. For example, the expansion and deployment of automatic weather stations has enhanced surface observation coverage in remote areas, while also providing the framework for observational consistency. It is important to note that ocean-surface observations have greatly increased over the past decade, with further increases likely through organized international efforts such as the Global Ocean Observing System (GOOS). Such efforts include: i) expansion of the moored buoy networks that began with the TAO array ~10 years ago; ii) increases in observations from ships of opportunity, ocean-surface drifters and ocean profiling technology.

3.3 Observing-System Simulation Experiments (OSSEs)

THORPEX will perform Observing System Simulation Experiments (OSSEs) that: i) guide the design of specific observing systems and the configuration of multi-sensor observing networks; ii) provide an assessment of the potential for future observing systems and innovative uses of existing systems to achieve major improvements in forecast skill; iii) test advanced data assimilation methods; iv) assess the relative role of observations and ensemble forecasting in improving the utility of weather forecasts. The current methodology consists of a long-time integration of an atmospheric simulation using a very-high-resolution (e.g., 10km horizontal and 100 vertical levels) numerical model to provide an assumed *'true'* state of the atmosphere, referred to as the *nature run* or *reference atmosphere*. The nature run needs to accurately mimic characteristics of the atmosphere such as average storm tracks, including the evolution and structure of synoptic and mesoscale events. Nature runs will be performed from observed atmospheric initial states for a variety of flow regimes containing life cycles of high-impact weather systems.

OSSEs will include an assessment of the potential impact of the observing technologies and sensor deployments, described above in Section 3.2. This assessment requires accurate representations of the observing-system attributes, performance limitations, and observational errors. An important component of OSSEs, that improves the interpretation of their results, is evaluation using a corresponding Observing System Experiment (OSE) using observations. THORPEX observational campaigns (Section 3.4) will provide the OSE data sets for comparison with OSSEs.

3.4 THORPEX Observing-System Tests (TOSTs), THORPEX Regional Campaigns (TReCs) and Global Prediction Campaigns

THORPEX field campaign activities will contribute to coordinating and facilitating the logistics to test and evaluate experimental remote-sensing and *in-situ* observing systems in THORPEX Observing-System Tests (TOSTs), THORPEX Regional Campaigns (TReCs) and global prediction campaigns.

THORPEX Observing-Systems Tests will test and evaluate experimental remote-sensing and *in-situ* observing systems, and whenever feasible, facilitate their assimilation into weather forecast systems. They will also be test beds for initial demonstrations of innovative uses of operational observing systems.

THORPEX Regional Campaigns are research and quasi-operational regional forecast demonstrations of 1-3 month duration contributing to the design, testing and evaluation of all components of interactive forecast systems. TReCs are organised and coordinated by regional consortia of nations under the direction of regional THORPEX Science and Core Steering Committees (Asian, European, North-American, and Southern-Hemispheric). TReCs will address high-impact weather events, such as: i) arctic storms and cold-air outbreaks; ii) extratropical cyclones, and tropical cyclones transitioning into extratropical cyclones; iii) warm-season heavy precipitation over Asia associated with subtropical frontal disturbances and monsoon circulations; iv) large-scale convection over the Indian and Pacific Oceans, and its influence on atmospheric flows within tropical and extratropical latitudes. Researchers and forecast centres from all regions will be encouraged to participate, at some level, in all TReCs. Figure 3.13 presents and example from the November-December 2004 North-Atlantic TReC during which targeted observations were deployed to improve a forecast of a land-falling extratropical cyclone over Northern Europe.

THORPEX participation in global prediction campaigns will provide demonstrations of all aspects of interactive forecast systems, over the globe for a season to one year, to assess the utility of improved weather forecasts and user products. This includes the THORPEX *Interactive Grand Global Ensemble, TIGGE*, which will integrate developments in observing systems, targeting, adaptive data assimilation, model improvements and a multi-model/multi-analysis ensemble prediction system. This global demonstration will be a complementary element within the World Climate Research Programme (WCRP) Coordinated Observations and Prediction of the Earth System (COPES), which itself addresses the observational and modelling requirements for the prediction of climate for two weeks and beyond. Results from regional and global campaigns will provide guidance through the WMO/WWW to agencies responsible for the design and implementation of the fixed and adaptive components of regional and global observing systems.

3.5 Research Objectives

The THORPEX Observing System research includes the following activities:

Develop and test new delivery systems for deploying *in-situ* sensors: These systems include: i) stratospheric balloons; ii) piloted and unmanned aircraft; iii) rocketsondes; iv) bi-directional radiosondes. Systems (i-iv) have the potential to provide additional soundings over oceans and remote regions, e.g., the Tibetan Plateau; Polar regions. The evaluation will include an early assessment of deployment logistics, the ability of systems to complement other observing strategies, and the cost of various measurement approaches. To be successful, the development of these delivery systems will often require concurrent sensor developments.

Carry out field-demonstrations of prototype remote-sensing systems for future airborne and satellite deployments: This effort will include observations with airborne radiometers, scanning radars and lidars to obtain: i) individual remote-sensor profiles for comparison with simultaneous *in-situ* soundings; ii) area-averaged profiles that simulate existing and future satellite's field-of-view. The initial demonstrations will be through TOSTs within diverse geographical regions and meteorological conditions: a significant requirement for satellite remote sensing system calibration and evaluation.

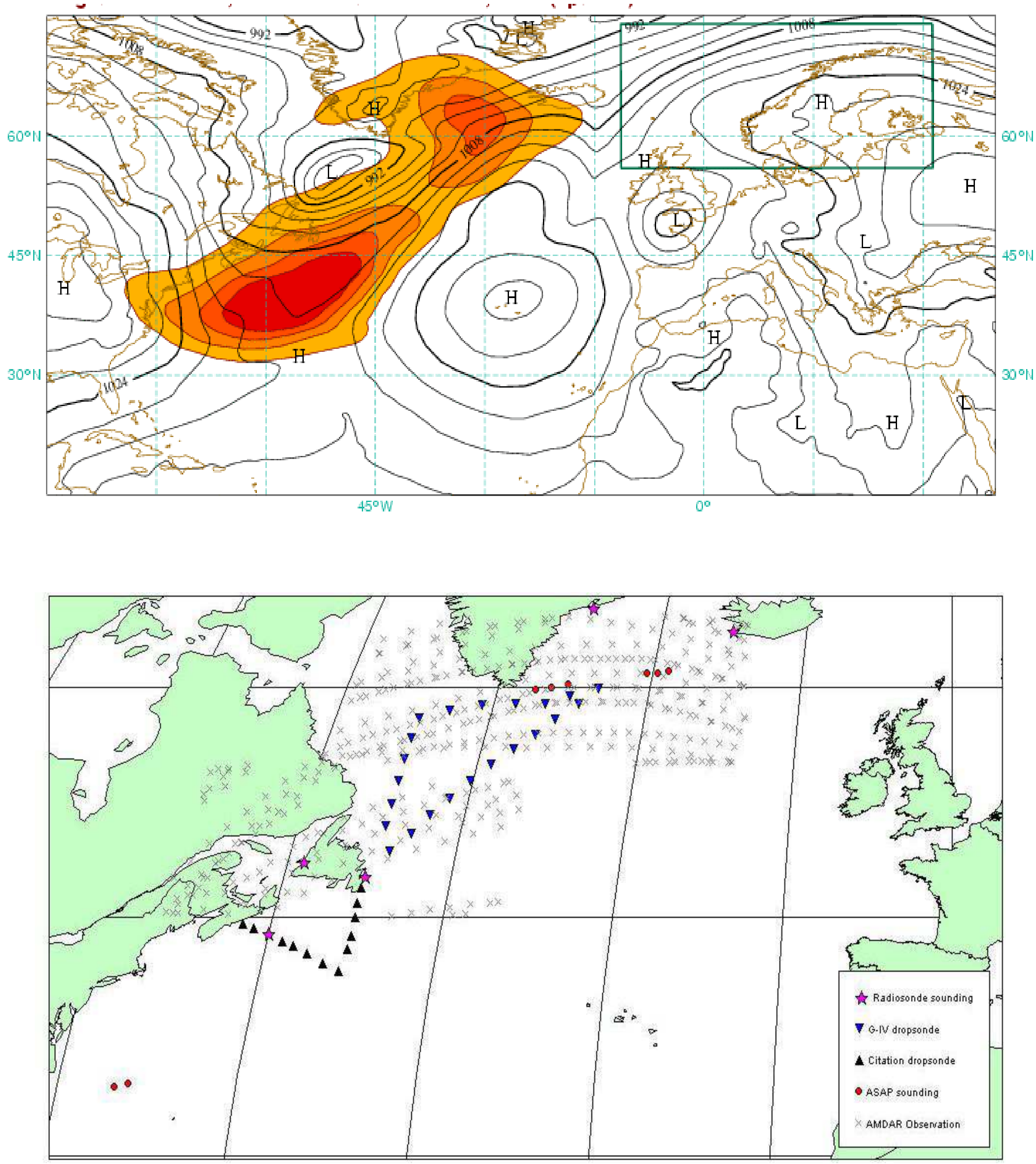

Fig. 3.13: Illustration of targeted observations from the THORPEX North-Atlantic Regional Campaign (NA-TreC) in November-December 2003. Upper panel: Sensitive-area calculation (colour shaded) using the TE-Singular Vector (dry T42) method defining the region for targeted observations at 1800 UTC 3 December 2003 for improving the 42-h forecast of a developing land-falling extratropical cyclone over Norway, verifying within the green box at 1200 UTC 4 December 2003. Lower panel: Targeted observations deployed to reduce initial condition uncertainty at ~1800 UTC 4 December 2004; dropsonde deployments from the NOAA/G-4 Univ. South Dakota/ Citation aircraft, downward and upward pointed triangles, respectively; 1800 UTC supplemental radiosonde assents, red stars, automated radiosonde assents from ships of opportunity (ASAP), red dots; targeted high spatial/temporal resolution commercial aircraft reports (AMDAR), grey Xs. This TReC was a coordinated campaign involving THORPEX European and North American regional participants, national forecast centres, and the European Coordinated Observing System (EUCOS); courtesy of David Richardson (UK Met. Office).

Provide observing-system characteristics for use in research and development of data-assimilation systems: This effort will contribute to the development of advanced assimilation systems for the new observing systems. This includes the characterization of performance limitations, errors, and representivity of specific observing systems. This coordination is critical for carrying out effective OSSEs and their comparisons with OSEs, TOSTs, TReCs, and global campaigns.

Organise the logistics and data management for TOSTs, TReCs, and global campaigns: This effort will resolve logistical difficulties, such as air-traffic control clearance for deployment of *in-situ* sensors and the use of lidars in areas of aircraft flight routing.. Data-management will facilitate access to experimental and operational data sets, in real time, and following field campaigns. The resolution of telecommunications and data-quality issues early in the systems development is central to the real-time delivery of experimental data sets to operational NWP centres in real-time, at an appropriate resolution.

Provide guidance to appropriate agencies on logistics of targeted observations: The results of experimental and operational research demonstrations of targeted observing systems will be provided to international and national meteorological agencies as input for consideration of adaptive programming of the global observing network. Adaptive programming could include: i) activation or repositioning of an existing satellite; ii) special satellite scanning schedules designed for high-time-resolution observations; iii) satellite spectral selection to facilitate testing of spatial density, frequency, and informational content; iv) the adaptive deployment of radiosondes, dropsondes, aerosondes, and driftsondes.

3.6 Reference Material

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The status and capabilities of current research and operational satellites can be found at:
http://www.wmo.ch/hinsman/satopstatus.html and http://www.wmo.ch/hinsman/CGMShome.html

4. Data Assimilation and Observing Strategies Research

4.1 Rationale

Data assimilation is a process leading to an estimate of the state of the atmosphere and ocean at a particular time, as well as a measure of the uncertainty associated with that estimate. This estimate may be used in a variety of contexts, e.g.: i) initial conditions (i.e., the *analysis*) for a numerical weather forecast; ii) verification for a prior forecast; iii) to establish a record for climate studies. The estimate is derived from both observations and a first-guess (or *background*) short-range forecast from the previous analysis, along with the statistics of the errors (measures of uncertainty) associated with observations and the background. A significant component of forecast error originates from uncertainty in the initial condition. This uncertainty arises from uncertainties in the observations, the background forecast and approximations in the assimilation scheme. Recent advances in many aspects of data assimilation and observing systems provide the opportunity for making substantial improvements in forecast skill. These advances include: i) greatly increased volume and quality of atmospheric observations, particularly from satellites; ii) adaptive observational techniques, or *targeting*; iii) improvements in assimilation algorithms, both in terms of their use of remotely-sensed observations and of their formulation. The THORPEX programme of research to capitalize on these advances is described below under *Targeting strategies (4.2)*; *Improved use of observations (4.3)*; *Adaptive data assimilation (4.4)*.

4.2 Targeting Strategies

In the last decade, strategies were developed that use forecast-system information to identify locations where additional observations would provide maximal improvements in the expected skill of forecasts. We refer to these as adaptive, or targeted, observing strategies, commonly called *targeting*. Targeting identifies localized areas, referred to as *sensitive regions*, in which the quality of the analysis has the greatest expected influence on the subsequent skill of the forecast. Targeting strategies are based on techniques that predict, prior to the actual measurements, the influence of an observation (or set of observations) on a subsequent forecast, in a statistical sense. This prediction involves calculating how observations will influence analysis uncertainty and how analysis uncertainty will grow and evolve during the forecast. In practice, these calculations involve significant assumptions and approximations. This has led to a number of different targeting techniques; some involve the adjoint of the linearised version of the forecast model (Bergot et al. 1999; Montani et al. 1999; Gelaro et al. 1999) or of the assimilation scheme (Doerenbecher and Bergot 2001, Baker and Daley 2000), whereas others manipulate ensembles of forecasts (Bishop et al. 2001; Szunyogh et al. 2000).

Figure 4.1 illustrates two examples of regions targeted for additional observations in order to improve 24-h forecasts for the west coast of North America. This illustrates the differences that can arise in the location of sensitive regions depending upon the targeting strategy being used. Further research is needed to evaluate the performance of the various strategies. As the results of such evaluations are inherently statistical, they must be averaged over many cases. There is potential for further improvements of targeting strategies by relaxation of certain assumptions, such as linearization, and by the use of enhanced statistical information from advanced assimilation schemes.

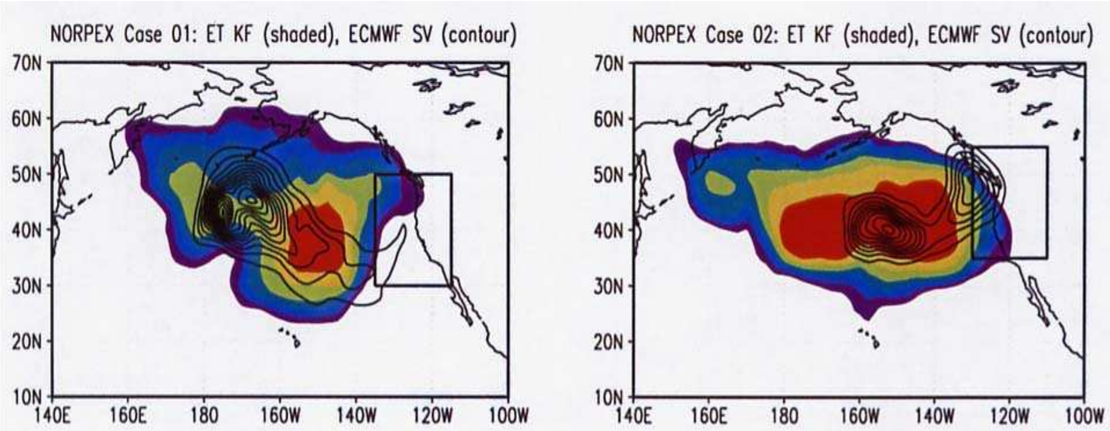

Figure 4.1: Illustration of the differences between the results arising from different targeting algorithms. Two cases from the NORPEX field experiment are shown; the intent is to select the observation location that will minimize the expected 24-h forecast error in the box on the right. Coloured regions indicate the sensitive regions as determined by an ensemble-based filtering approach; contours indicate region of increasing observation sensitivity as determined by an adjoint-based singular vector approach (from Majumdar et al., *QJRMS*, **128**, p 2527).

Observing systems can be targeted in a variety of ways. Examples include the control of the sampling rate of satellite sensors or the timing and location of mobile upper-air soundings. Targeting techniques also have the potential for much broader applications. Besides providing guidance on where additional observations would be most effective for improving forecast skill, targeting can also be used to determine which observations are to be discarded, i.e., to conduct effective *thinning* of the observations. This capability will become increasingly more important, given the very large numbers of observations that will be available from next-generation satellites. The ability to quantify the influence of a given observation on analysis or forecast uncertainty also provides the basis for assessing existing observational networks and providing recommendations for their future improvements.

It is conceivable that nested high-resolution models (see Figs 2.12-2.14) could be used to target localised, dynamically "sensitive" regions identified by targeting with global models as in Figs.3.12; 4.1. These nested models would be interactive with the outer courser-resolution global model and couple to the global assimilation cycle. Improved representation of dynamical and physical processes within the targeted high-resolution region has the potential to reduce uncertainty in the global forecasts, both within and external to the high-resolution mesh. This could provide an improved background analysis for assimilation of new observations. Another consideration would be to utilise the high-resolution grid to assimilate high- spatial/temporal resolution targeted observations, though this may not be straight forward due to differences in background error between the global and high-resolution domains.

4.3 Improved Use of Observations

Forecast skill has significantly improved as the result of the development of innovative methods for assimilating observations. An example is the large benefit derived from assimilating radiances from satellites rather than the retrieved profiles. There are substantial opportunities to further improve the assimilation of observations, particularly those in sensitive regions. A key challenge will be to utilize effectively the large, and potentially overwhelming, volume of observations such as from next-generation satellites. One promising technique is to extract the most relevant information from high spectral-resolution sounders by selecting either specific channels or linear combinations of channels that contain the greatest independent information. Another approach is to use targeting to identify which subset of the total observational network is critical in determining forecast skill. Both of these techniques can be combined to target the most useful channels available from the high spectral-resolution channels. For example, Figure 4.2 shows examples of channel selections for the future advanced sounder IASI on board the European platform METOP. These 300 channels were selected out of 8461 for assimilation in a sensitive area. Panel a) presents the channels selected using an iterative method optimising the information extracted from the observations following Rabier *et al.* (2002), and panel b) presents the channels selected using a method based on targeting principles following Doerenbecher and Bergot (2001). One clearly sees that the first method tries to improve the knowledge of the atmosphere throughout the pressure range, whereas the method focusing on sensitive structures mainly targets the low-level temperature.

Figure 4.3 illustrates the relative impact of observations assimilated at 0000 UTC on a measure of global forecast error. The dominant role of satellite data in the southern hemisphere is evident, while rawinsondes remain important in the northern hemisphere.

Another challenge is to quantify observation errors in terms of both their magnitude and covariances. Assimilation of high-resolution observations can degrade the analysis if their horizontal correlations are unknown and ignored. Other outstanding issues include specifying errors for moisture observations and characterizing representativeness errors, which arise when the measurements include scales or processes that are not represented in the forecast model.

It is believed that improved assimilation of precipitation and cloud processes will provide increases in forecast skill. Observations of these processes, such as from passive and active microwave sensors, are plentiful, but their use in the forecast system has been limited both because radiance/reflectivity is a not well known function of precipitation and cloud, and because the representation of precipitation and clouds in forecast models is poor. Improving and extending the use of cloud and precipitation observations may be crucial in the longer term.

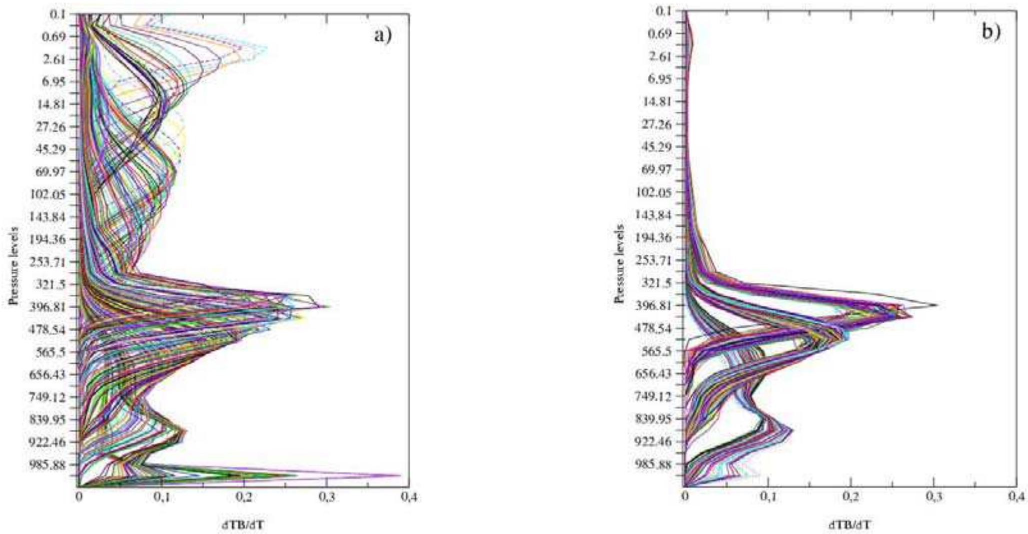

Figure 4.2: Weighting functions as a function of pressure level of the 300 IASI channels selected for assimilation for a given profile in a sensitive area. Panel a) uses a channel selection method optimising the information content of the observations. Panel b) focuses on the retrieval of a sensitive pattern located below 300hPa through the use of a Kalman Filter Sensitivity approach (from Fourrié and Rabier, 2003).

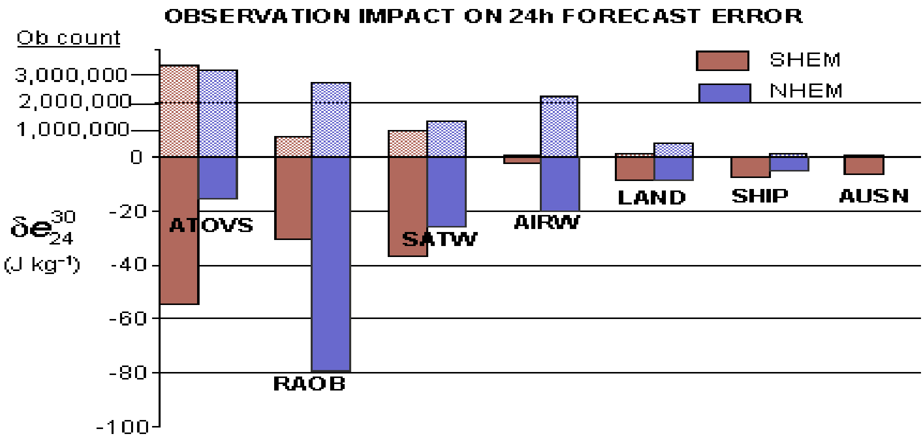

Figure 4.3: Impact of the type and number of observations *(upper, light shaded bars*) on 24-h forecast error (*solid shaded bars*) in the Southern and Northern Hemispheres (*brown* and *blue*, respectively) from data assimilated at 0000 UTC during June and December 2002. The value δe_{24}^{30} is the difference between quadratic measures of the 24-h and 30-h global forecast errors estimated using adjoints of the NOGAPS forecast model and NAVSDAS data-assimilation system. Negative values of δe_{24}^{30} indicate that the forecast error of the analyzed trajectory is less than the forecast error of the background trajectory. Observing systems: **ATOVS**-temperature retrievals, **RAOB**-rawinsondes, **SATW**-cloud and feature-track winds, **AIRW**-commercial aircraft observations, **LAND**-land surface observations, **SHIP**-ship surface observations, **AUSN**-synthetic sea-level pressure data (from Langland and Baker 2004).

4.4 Adaptive Data Assimilation

There have been significant advances in the development of four-dimensional assimilation techniques, such as four-dimensional variational schemes (4D-Var) and the ensemble Kalman filter (EnKF). Such schemes are adaptive in the sense that they propagate information about background-error covariances and allow the influence of an observation on the analysis to depend on the evolving state of the flow and on the locations and uncertainties of past observations. These schemes also form the basis for techniques to quantify the importance of a given observation to future forecast skill, which underlie targeting strategies. Analysis and forecast experiments (Bergot 2001; Hamill and Snyder 2002; Desroziers *et al.* 2003) show that these techniques are more efficient that 3D-Var in extracting information from targeted observations. Figure 4.4 illustrates the importance of background-error covariances and the potential advantages of an adaptive assimilation scheme that incorporates flow dependence.

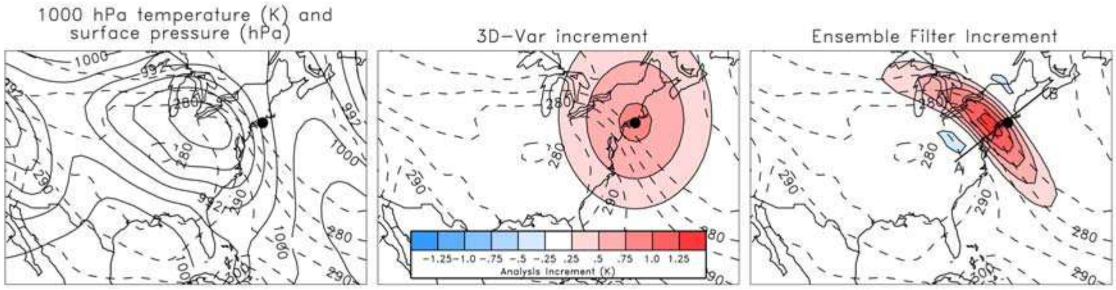

Figure 4.4: Illustration of the impact of background-error covariances. The surface pressure and 1000 hPa temperature of the model first guess are shown in the left-hand panel. Consider the correction, or "increment," to an observation that is 1K warmer than the first guess at the location denoted with a dot. 3D-Var increments (middle panel) are isotropic, largest at the observation location and smaller with increasing distance from the observation. Ensemble-filter increments use flow-dependent background-error co-variances that recognize that errors are more strongly correlated along the warm front than across it; hence corrections are stretched out along the frontal zone and maximized not at the observation location, but nearby where the gradient is tightest (courtesy of Tom Hamill NOAA/CDC).

4.5 Research Objectives

The following research activities will focus on developing the required advances in the use of observations, targeting methods and data assimilation:

Improved use of observations

Quantify observing-system errors: Estimate observation errors, especially errors of representativeness, which are likely to be flow-dependent and correlated between nearby observation locations. Test the effects of improved observation-error statistics on forecast skill.

Develop methods for efficient utilization of high-volume datasets: Develop and test adaptive methods for thinning large datasets so that the most useful observations are retained. Develop techniques for assimilating high-resolution observations, including proper characterization of horizontal correlations and averaging (or *super-obing*) of nearby measurements. Develop techniques to extract the maximum information content from hyper-spectral sounders, and other observing systems when, for example, it is computationally impractical to assimilate radiances from all channels.

Improve the use of geostationary satellite observations: Improve the use of visible, infrared and water vapour image-sequences to infer wind information. This may require innovative approaches, such as interactive height assignment methods or the use of imagery sequences directly in the assimilation.

Improve assimilation of physical processes: New methods to assimilate certain satellite observations (e.g., those from active microwave sensors and cloud and precipitation imagery) are required in order to infer physical processes such as diabatic heating.

Targeting techniques

Refine targeting strategies: Perform observing system experiments (OSEs) and observing system simulation experiments (OSSEs), including demonstrations with data sets from field experiments, to evaluate the performance of targeting strategies. This evaluation will lead to refinements in targeting strategies.

Generalise existing targeting techniques: Account for non-linearity and non-normality, especially for longer forecast lead times (>2-3 days) and/or in flow regimes where physical processes such as moist convection and clouds play a dominant role.

Test targeting with limited domain high-resolution models: Explore the use of high-resolution regional models, with two-way interactive boundaries between the global and high-resolution domains, to target localised, dynamically "sensitive" regions identified within global predictions. The objectives are: i) to provide improved background analyses for global-model data assimilation; ii) to assimilate enhanced spatial/temporal resolution observations in targeted regions.

Test targeting algorithms for a wide range of weather systems: Candidate forecast problems include: i) hurricane track and intensity forecasts; mid-latitude summer heavy rainfall episodes; ii) and extended range (week-two) predictions. This should include research on the dynamical processes that propagate information spatially and temporally between the targeted regions and the selected weather events.

Support TOSTs, TReCs and THORPEX participation in global campaigns: Provide guidance for the deployment of individual and composite (multi-sensor) observing systems during THORPEX Observing System Tests (TOSTs), THORPEX Regional Campaigns (TReCs) and global prediction campaigns.

Design observational networks: Develop and test systematic and objective techniques for the design of observing networks**.** Quantify the required accuracy and resolution for the measurement of various quantities, and evaluate trade-offs between accuracy and resolution, or between resolution and areal coverage.

Adaptive data assimilation

Improve background-error covariances in existing assimilation schemes: Test improved, flow-dependent models of background-error covariances in techniques like 3D-Var and 4D-Var.

Develop methods for cycling flow-dependent background errors: Develop and test assimilation methods that explicitly allow for changes in background-error covariances from one analysis to the next, such as Kalman-filter/4D-Var hybrids or ensemble-based schemes.

Develop adaptive quality control: Develop and test adaptive quality control algorithms that can utilize information provided by flow-dependent background-error covariance estimates.

Incorporate model uncertainty into data assimilation procedures: Develop and test ways of incorporating the effects of model uncertainties leading to systematic forecast errors and the effects of unresolved scales into the specification of background-error covariances for data assimilation schemes. Develop statistical algorithms to "tune" model uncertainty in assimilation algorithms and to diagnose and correct model bias.

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5. Societal and Economic Applications Research

5.1 Rationale

Weather forecasts provide timely information about atmospheric conditions that affect society, economy and the natural environment. Skillful forecasts allow society to mitigate the consequences of high-impact weather and to respond efficiently to day-to-day weather. Many applications of weather forecasts involve translating predicted meteorological parameters (e.g., wind speed; temperature; precipitation) at specific spatial and temporal scales into societal/economic attributes of the natural or human environment such as energy demand, transportation efficiency, demands on health services, water resources, pest infestations, and wildfire air quality. It is important for weather forecast products to continue to meet the diverse applications and the needs of society.

From an economic perspective, weather forecasting may be considered an *"infra-technology,"* producing valuable information for economic and technological activities (Williams and Smith 2003). The impact of weather forecasts on societal and economic activities is a consequence of several forecast elements: i) *content*: relevance of product information to the users, ii) *distribution*: product dissemination on spatial and temporal scales sufficient for action, iii) *communication*: product formats that users can comprehend and interpret, iv) *recognition*: recognition by users that the information has value, and v) *response*: actions taken by users in response to the information. These elements are links along a chain of action. If any one link is broken, then the impact and the value of the forecast information will be diminished. Socio-economic research can identify weaknesses in these links and lead to the development of new methods for enhancing the use and value of weather information.

THORPEX Societal and Economic Applications (SEA) research will contribute to the development of forecast systems that are responsive to the needs of users of weather-forecast information, with an emphasis on *high-impact weather forecasts*. These forecasts include predictions of extreme weather hazards, such as winter storms (Fig. 5.1) tropical cyclones and, as well as non-extreme weather, such as, periods with above or below average temperatures or precipitation. High-impact weather forecasts are defined by their effects on society and the economy and, more specifically, on the diverse sectors that utilize weather information. These sectors include emergency management; food production; water management; private sector providers; health services; energy; leisure tourism; transportation; the general public. SEA research will assess how weather forecasts are utilised by these various sectors and how this utilisation can be improved. This will require identifying what constitutes high-impact weather forecasts and estimates of their economic and societal value. Socio-economic research and methods will be implemented to: i) evaluate the net economic benefits of THORPEX improvements in weather forecasting; ii) assess and improve the content, distribution, communication, recognition, and responses to weather forecast systems and information; iii) assist with product development and the transfer of tools and knowledge, especially to developing countries.

Fig 5.1 A photographic collage depicting the societal, economic and ecological impacts of severe weather associated with four Rossby wave trains that encircled the globe during November 2002.

5.2 Societal Impacts and Economic Benefits of Weather-Forecast Information

Use of weather forecast information benefits a variety of industries and markets, in addition to the public at large. Examples of the use of weather forecast information include: i) efficiency of energy production and transmission to meet energy demand; ii) protection of infrastructure and positioning of utilities and emergency-preparedness equipment and personnel; iii) efficiency of agricultural production processes (e.g., planting, harvesting and the mitigation of the effects of freezing weather); iv) planning and allocation of resources by travel and leisure industries; v) management and routing for land, sea, and air transportation; vi) allocation of health service resources to target weather-sensitive health conditions (Fig.5.2), such as influenza and asthma; vii) allocation of resources to target transmission of plant, animal or human diseases; viii) management of water resources; ix) efficiency of and decision making in commodity markets (energy, agricultural and industrial); x) environmental decision making and ecosystem and natural resource management.

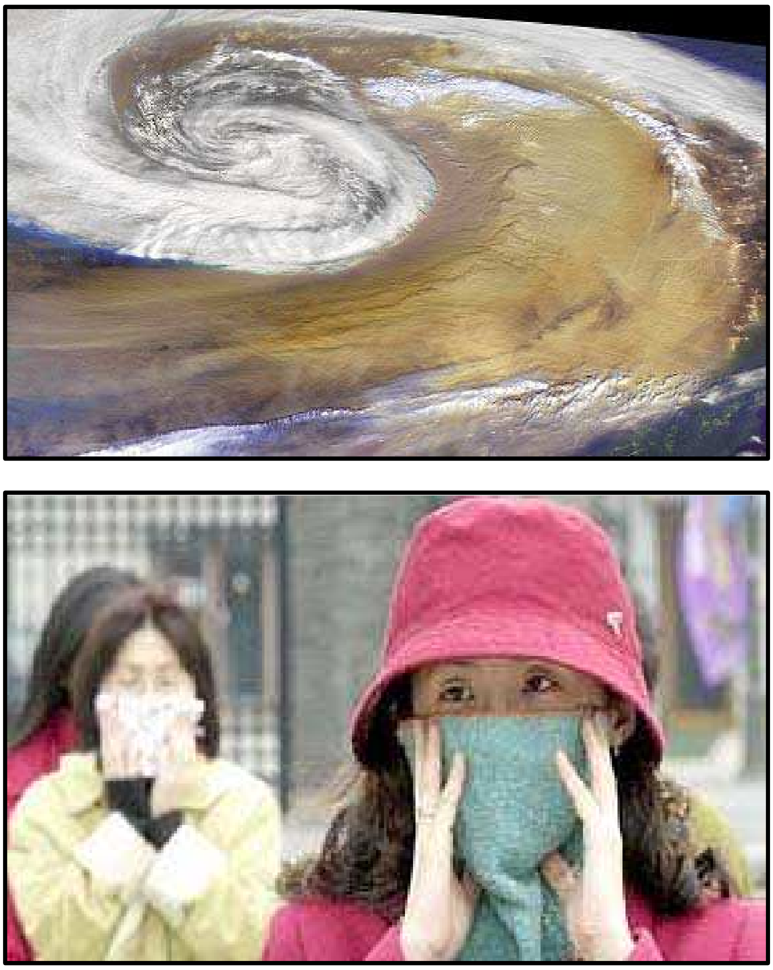

Fig. 5.2 Respiratory distress from a dust storm over eastern China, driven by cyclone development in the lee of the Tibetan Plateau during early April 2001. *Upper panel:* MODIS visible satellite image on 7 April 2001 showing the major cyclone; cloud circulation (white colors), dust storm (brown colors). *Lower panel:* two women covering their faces in their effort to mitigate the health-threatening impact of poor air quality.

The value of weather forecast information has been assessed for a relatively selective set of users, such as those who make *binary decisions*, that is, whether or not to protect a crop or de-ice a motorway (Figs.5.3; and 5.4). SEA research will extend such value assessments to a broader set of weather events, forecast products, and decision makers, using a variety of socio-economic research methods. This will include addressing outcomes that involve continuous variables, such as the quantity of electricity to be generated. Together, these assessments will contribute to the improved use and value of forecast products and the design of forecast systems. When combined with information from a similarly thorough investigation of the cost of these improvements, knowledge of the societal impacts and economic value of weather information can influence decisions regarding the allocation of observational, computational, and research resources. Such decisions could include: i) forecast-model computational resolution versus number of ensemble forecast members; ii) targeted versus non-targeted observations; iii) standard or rapid update of the data-assimilation cycle. Knowledge that the forecast system itself is responsive in this way will enhance both the participation and the degree of feedback from users and providers of weather forecast information.

Fig. 5.3: A rare heavy snowfall for Oklahoma City Oklahoma, USA resulting in a major disruption in motor traffic, property loss, and personal injury (courtesy Bill Mahoney NCAR/RAP).

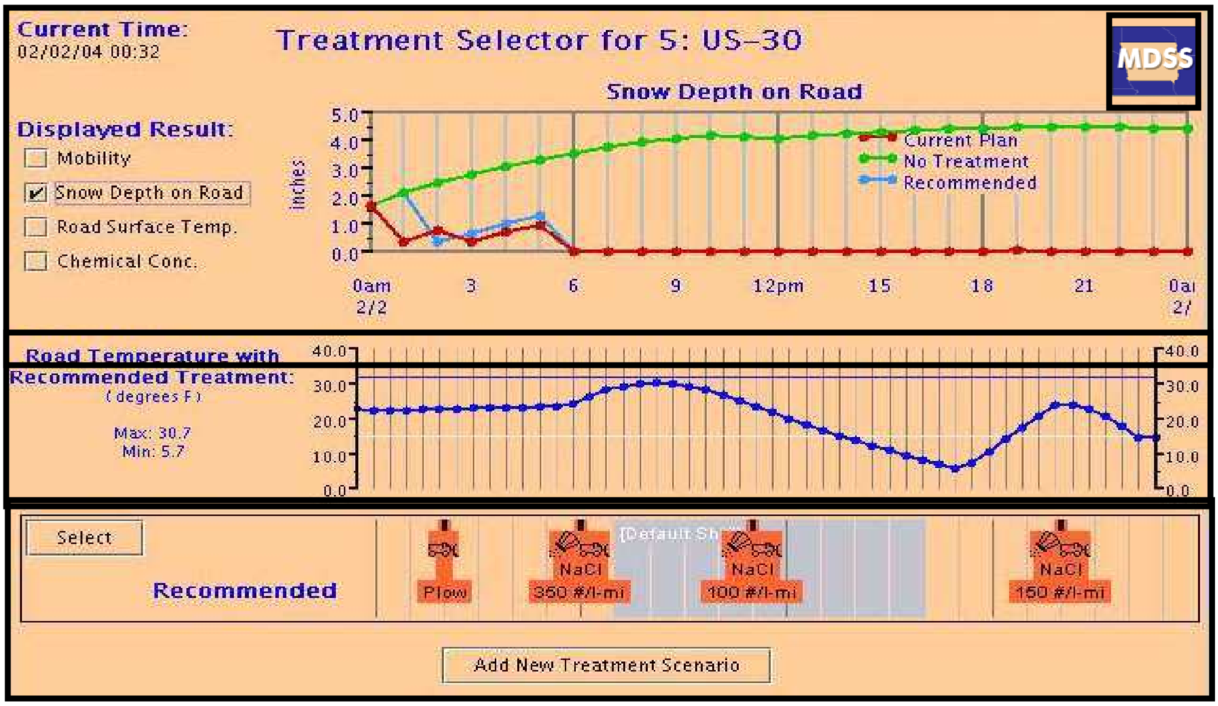

Fig. 5.4: Real-time display from the winter road Maintenance Decision Support System (MDSS) showing the predicted 24-hr snow depth, road temperature, and treatment plan for snow impact mitigation on State Highway 30 near Ames, Iowa. This system is used by highway maintenance personnel for planning de-icing operations. this example, the system recommends a single snow removal operation followed by several salt applications of between 100 and 350 pounds per driving-lane mile (courtesy Bill Mahoney NCAR/RAP).

5.3 Research Objectives

A key objective is to develop a framework within which researchers in the meteorological research, economic, policy and social science communities will interact with operational forecast centres and users of weather forecast information. This interaction will contribute to the development of improved forecast systems designed for the diverse geographic regions involved in THORPEX. Research findings will be made available for training and educational material to all nations.

THORPEX Societal/Economic Applications research will: i) define and identify high-impact weather forecasts; ii) assess the impact of improved forecast systems; iii) develop advanced forecast verification measures; iv) estimate the cost and benefits of improved forecast systems; v) contribute to the development of user-specific products; vi) facilitate the transfer of THORPEX advances to forecast centres throughout the world. This research will be conducted through collaboration with forecast *providers* (operational forecast centres and private-sector forecast offices) and forecast *users* (energy producers and distributors, transportation industries, agriculture producers, emergency management agencies and health care providers). It will provide wide-ranging information on what constitutes high-impact weather forecasts for individual sectors and users and assist in establishing research priorities within all elements of THORPEX.

Identify high-impact weather forecasts: This effort will identify the global-to-regional weather forecasts that have major effects on selected sectors of society and economies within various geographical regions. It will address the effects of recent high-impact weather forecasts in terms of the *economic consequences* (such as property damage, loss of crops or livestock, and interruption of transportation services) and the *human consequences*, such as illness from heat or cold, contamination of drinking water by floods, and damage to electric power distribution. Studies will investigate which forecasts have the greatest *marginal value*, i.e., the greatest added value to users and society in mitigating losses, increasing gains, or improving the management of resources. Responses to subsequent weather forecast products and the value of potential improvements will be assessed from the perspective of a range of current and potential weather-sensitive sectors.

Assess the impact of improved forecast systems: The identification of high-impact weather forecasts will provide the basis for studies estimating the marginal value of *improvements* to forecast systems. These studies will be made for various types of weather forecasts and lead times, diverse user groups or societal/economic sectors and different geographic regions. Estimates will be made of the marginal value of improved weather forecast information from databases, such as archived forecasts and re-forecasts using modern models for past weather events, Observing System Simulation Experiments (OSSEs) and forecasts from THORPEX field campaigns. These studies will estimate the range of marginal gains to be derived from a variety of forecast system improvements within different sectors of society.

Develop advanced forecast verification measures: The development of user-relevant verification of weather forecast information is a prerequisite for evaluating the societal and economic impact of improved forecast systems. Some of the most widely used verification measures in use by operational forecast centres to evaluate forecast skill (such as the 500-mb anomaly correlations between the model forecast and the model analysis) are of limited value to decision-makers who use weather forecast information. The appropriate verification measures vary with the user's requirements, and are generally related to *vulnerability* or *opportunity* for a given user, industry, location, or segment of society. *User-relevant forecast measures* include: i) site- and time-specific measures e.g., time of passage of a front, transition from rain to frozen precipitation, and timing of air pollutants above or below critical concentrations; ii) integrals over space and time, e.g., transportation travel times, power-generation efficiency, hours of air pollutants above critical concentrations, and duration of hazardous high or low temperatures. Such measures are often a non-linear function of multiple meteorological variables (wind speed, temperature, humidity, visibility, sea state, etc.) and non-meteorological variables (type of equipment in place, topography, and land use). THORPEX SEA research will participate in developing these measures, and in implementing them as part of forecast systems, so that forecast-system improvements can be evaluated according to their value to societies and economies around the globe.

Estimate net benefits of improved forecast systems: Estimating the costs and benefits of implementing potential THORPEX advances in daily forecast operations will require: i) estimating potential forecast improvements from various forecast system implementations; ii) estimating marginal costs and benefits of the improvements; and iii) combining this information in a way that can be used in making decisions on the design of forecast systems. In order to provide these estimates, THORPEX will build on existing methods for evaluating costs and benefits, and SEA research described above. It will also identify information required to arrive at: i) detailed estimates of costs of implementing different observing systems; ii) a comprehensive evaluation of expected forecast improvements measured with user-relevant verification.

Develop new user-specific weather products: THORPEX SEA research will assist in the development of new methods to translate predicted meteorological parameters into quantities of interest to specific user sectors, so that improvements to forecast systems will be responsive to society's diverse weather information needs. This will include developing methods where the outcomes of interest to users are continuous functions of meteorological conditions and where operational probabilistic (rather than deterministic) forecast information can be utilized. Studies on improvements in current probabilistic forecast systems will provide information on multivariate, spatial and temporal information critical to many social and economic applications. SEA research will develop methods to overcome current barriers to improved communication, recognition, and use and value of weather forecast information, for example, difficulties utilizing probabilistic forecasts in decision-making and warnings integrated over space or time scales incommensurate with user requirements.

Facilitate transfer of THORPEX advances to forecast centres throughout the world: SEA efforts will encourage and facilitate the distribution of THORPEX research findings and the use of advanced weather forecast information to user sectors and forecast providers throughout the world, with special emphasis on developing countries. This will include working jointly with forecasters and users in developing countries, as well as assisting in training in the use of the new methods developed by SEA research. In addition, SEA techniques and evaluations of forecast systems will be made available to governments and international agencies for use in decisions about allocations of resources for improved weather services. The transfer of THORPEX research findings will not only benefit societies and economies throughout the world, but will also increase public awareness of the value of weather forecast information to society.

5.4 Reference Material

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