The Known, the Unknown and the Unknowable in the Predictability of Weather

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Preface

The Alfred P. Sloan Foundation sponsored a workshop on "The Known, the Unknown and the Unknowable in Weather Predictability." This workshop was organized by Professors David Straus, J. Shukla and Ben Kirtman of George Mason University and the Center for Ocean-Land-Atmosphere Studies.

The participants, including many of the most respected experts in weather predictability, met and engaged in both detailed and broad discussion of our vision of weather prediction and predictability in the present and future. Even nature attempted to attend the workshop: a snowstorm of record-breaking proportions shut down the Washington DC area before and during the workshop, disrupting travel plans and forcing the use of remote speaker-phone / e-mailed Power Point presentations!

Jesse Ausubel, representing the Sloan Foundation, opened the workshop by noting that it is very helpful in many fields to review what is known and what is unknown. In the natural sciences in particular, some things are just too large to know (e.g. require too much data or too much computation), while others are truly unknowable. Understanding what we know and don't know, how to move that boundary, and what component of what is unknown is in fact knowable are all very helpful activities to both scientists and to society at large.

The Workshop Prospectus and Background are given in Section 1, while a summary of the discussion of the Workshop is given in Section 2. The list of participants and the Agenda are given in the Appendix.

1 Workshop Prospectus and Background

It has long been assumed that the upper limit of weather predictability for the synoptic and larger scales is one to two weeks. This limit seems to be consistent with practical experience, and is generally accepted by the forecasting community. Many assume that the theoretical support for this limit rests on the theory of isotropic, homogeneous quasi-geostrophic turbulence, as crystallized in the works of, for example, Lorenz, Leith and Kraichnan. In fact a careful reading of these important works leads to a startling and surprising conclusion: *The ultimate limit of weather predictability rests on a knife's edge.* For an equilibrium energy spectrum of $E(k) \sim k^{-3}$ (or steeper), one can in principle extend the range of predictability by confining the initital errors to smaller and smaller scales, with the associated amplitudes scaled by the ever decreasing equilibrium variance. However, for an equilibrium energy spectrum *less steep than* $E(k) \sim k^{-3}$, the errors will cascade up-scale to contaminate the largest scales in about two weeks, independent of how small we make the scale and amplitude of the initial errors.

It is worth remembering that these conclusions can be understood in terms of the concept of the "eddy turnover time", the characteristic time τ associated with eddies of a particular scale: $\tau(k) \sim [k^3\, E(k)]^{-1/2}$. The characteristic turbulence time of errors initially on a small scale given by wavenumber $k = k_s$ to propagate up-scale to a large scale characterized by wavenumber $k = k_1$ is given by:

$$T = \int_{k_1}^{k_s} d(\log k)\, \tau(k) \tag{1}$$

With $E(k) \sim k^{-p}$, this integral will converge as $k_s \to \infty$ for $p < 3$, and for $p = 5/3$ for example, the integral converges rapidly. Thus the time T taken for errors to propagate from k_s to k_1 is finite and limited, indicating a fundamental to the range of predictability. For $p \geq 3$, the integral diverges as $k_s \to \infty$, and thus the range of predictability is not limited.

That the observed energy spectrum of the atmosphere is close to $E(k) \sim k^{-3}$ for the synoptic scales, consistent with the theory of quasi-geostrophic turbulence theory, indicates that we can *not* conclude that real weather predictability is fundamentally limited. This dilemma was perhaps obscured from general recognitition because one of the earliest turbulent predictability calculations was carried out for an unrealistic synoptic scale spectrum of $E(k) \sim k^{-5/3}$.

These quasi-geostrophic considerations are limited in several ways. One is that they ignore the imhomogeneity of the atmospheric flow (the presence of stationary waves) and the low frequency flow associated with weather regimes. Another limitation is that smaller scales involve dynamics which are distinct from those of quasi-geostrophy. Both of these limitations are next addressed.

One of the great hopes of extended-range weather prediction lies in the potential predictability of the *grosswetterlage*, or weather regimes. These regimes, characterized by the organization of the synoptic scales by distinct large-scale circulation patterns, have remained elusive. While their existence is widely accepted, careful definitions based on modern statistical techniques (e.g. cluster analysis, finite mixture modeling) have been severely hampered both by lack of a sufficiently long observational record and by atmospheric model errors.

The possibility of extending large-scale predictability beyond two weeks provides a significant motivation for an intensive effort to better understand weather regimes, and to explore the predictability of their residence times, and of transitions between them. How can we approach this formidable task as a community? Can we quantify the expected gains in predictability?

A more detailed look at the small scale dynamics may also help us to resolve the issue of the intrinsic predictability of the atmosphere. Observational studies have suggested that scales in the range of $\sim 800 - 100$ km do not follow the $E(k) \sim k^{-3}$ spectrum of the synoptic scales, but one closer to $E(k) \sim k^{-5/3}$. The associated dynamics seem to involve both gravitational and rotational modes. Some theories suggested a possible *up-scale* energy transfer from convective forcing. More recent observational and theoretical work points to a mesoscale dynamical regime in which the flow becomes vertically structured; thinner and thinner layers spontaneously develop until instability sets in. Here the energy cascade is in the *down-scale* direction (energy flowing from large to small scales). While the interpretation of the $E(k) \sim k^{-5/3}$ remains controversial, attempts at understanding the implications for extended range weather predictability have been sparse.

Turbulence theory, the nature and predictability of weather regimes, and the role of the small scales in propagating error growth to larger scales, are all key issues in answering the question: For how long can we predict weather, at any level of detail? Do we know the answer? Can we know the answer? The importance of the central question of the fundamental limit of predictability can not be overstated, for upon it rests the distinction between being forever unable to extend weather forecasts beyond one or two weeks, or the possibility to go beyond this with improved understanding of atmospheric dynamics and improved observations.

2 Workshop Discussion

2.1 Theoretical Limits to Weather Predictability

One of the starting points of the workshop was the pioneering work of Professors Lorenz, Lilly and others nearly 50 years ago on homogeneous two-dimensional and quasi-geostrophic turbulence. This work indicated a deep connection between the energy as a function of spatial scale (the spectrum) of atmospheric disturbances and the prospects for extending the range of useful predictability as uncertainties in our knowledge of the initial atmospheric state become smaller and smaller. The observed atmospheric spectrum, which varies as k^{-3}, where k is wavenumber, forms a kind of predictability boundary: spectra which are steeper (relatively less energy in the smaller scales) are associated with enhanced predictability (with no theoretical limit), while spectra which are less steep (relatively more energy in the smaller scales) lead to a hard limit (of about 2 weeks) in the ultimate range of predictability.

This idealized homogeneous theory, coupled with observations (starting in the late 1980s) that the small synoptic scales are indeed characterized by a shallower spectra $E(k) \sim k^{-5/3}$, and even more importantly with the perceived lack of progress in increasing the useful range of real weather predictions during the 1990's, suggested a real urgency in trying to mesh theory and practice.

Motivated by this urgency, Professors Lilly and Bartello and Drs. Vallis and Lindborg reviewed theoretical and observational aspects of turbulent spectra and their interpretation for predictability. Dr. Vallis discussed various "flavors" of turbulence beyond the standard two-dimensional (or quasi-geostrophic) theory, and in particular pointed out that surface quasi-geostrophic flow, which we can think of in terms of temperature advection along the surface or the tropopause, is associated with quite shallow spectra, $k^{-5/3}$ and k^{-1}, for different ranges of scales. Such shallow spectra may indicate that certain types of disturbances are associated with very little predictability, and raises the question of whether the predictability becomes dependent on the type of flow present at a given time in the atmosphere.

The role of divergent modes was taken up by Professor Bartello, who presented theoretical developments meant to explain the observed $k^{-5/3}$ spectra. He concluded that if the severe limitations of quasi-geostrophic turbulence theory are relaxed somewhat, the role of divergent modes (involving gravity waves) becomes important, and that they might provide an explanation of the observed shallow spectrum at small synoptic scales. Importantly, since the important weather-containing modes of the atmosphere are predominantly not the divergent modes, the shallow spectrum does not necessarily indicate a limitation to weather predictability.

Dr. Lindborg presented a detailed turbulence-based analysis of aircraft observations, and showed that even ignoring the divergent modes, the traditional turbulence arguments do not correctly explain the observed direction of energy transfer in the $k^{-5/3}$ range: the observed energy transfer is from large to small scales, opposite to what the standard theory predicts.

The discussion stimulated by these results emphasized the limitations of any of the turbulence based approaches which ignore the critical roles of rotation, of moisture and latent heat release, of the inhomogeneous and interactive forcing of the atmosphere and of the localized nature of error growth. The relevance of the hard predictability limit of homogeneous quasi-geostrophic theory to the complex atmosphere is clearly in question.

2.2 Weather, Chaos and Weather Regimes

Professor Lorenz's unique perspective on weather and chaos provided an instructive contrast to homogeneous turbulence by emphasizing the inhomogeneous nature of atmospheric chaos. While the community didn't appreciate the role of chaos in weather fluctuations 50 years ago, there began to be an appreciation of the fact that some atmospheric quantities are more predictable than others, and that predictability is highly dependent on the current situation. Certainly that appreciation has grown over the years, as the concept of "weather regimes" has become better understood. Regimes are distinct episodes in weather patterns whose lifetime exceeds that of individual disturbances. Transitions from one regime to another are irregular and hard to predict. Since the simplified chaotic systems presented by Professor Lorenz tend to emphasize non-linearity and lack of homogeneity in the flow, they are perfect tools to illustrate this regime paradigm.

A more realistic approach to weather regimes was taken by Dr. Molteni, who took a hard look at the record of observed fluctuations. He concluded that the existence of weather regimes in the observed data is a reasonable working hypothesis, and that high resolution forecast models have shown evidence that the presence of regimes actually impacts predictability. Predictions are more successful when the observed atmospheric state is in preferred regimes.

One can take a bolder step, and ask "Is a system with regimes more (or less) predictable than one without regimes?" The difficulty of finding an answer arises from the fact that dynamical systems with and without flow regimes usually differ in a number of aspects which are themselves relevant to the predictability problem. However, recent model evidence has shown that the atmosphere may alternatively behave as a single-regime or a multi-regime system under naturally generated changes in the SST boundary conditions, such as those related to El-Niño. This opens the possibility of performing predictability experiments involving similar initial states but distinct SST boundary conditions in order to address this question.

2.3 Advanced Current Operational Weather Prediction

A very broad overview of progress, problems and prospects for improving weather predictability in the context of state-of-the-art numerical weather prediction was offered by Drs. Bengtsson and Hollingsworth. There was clear agreement that the overall forecast skill of the synoptic and larger scales has substantially improved in the past several years, following a period during the early 90's in which little progress was seen. Southern Hemisphere extra-tropical forecasts have become almost as accurate as those in the Northern Hemisphere, and especially in the category of the poorest forecasts marked improvement has been seen.

Further, it seems that the various forecast models have converged in terms of accuracy.

The increase in accuracy of mid-latitude forecasts holds for forecast ranges of 1 - 10 days, but it is especially dramatic at day 1, when the forecast errors are much smaller than a decade ago. The improvement in the day 2 forecast is not as dramatic, so that in fact the error growth rate at day 1 has increased! The medium range errors grow about as quickly as they did in the forecast systems used a decade ago. The improvement in the day 1 forecast is so significant that even with the larger error growth rate at day 1, the level of error of forecasts from days 2 to 10 has decreased.

In the tropics, while improvements in the short-range forecasting of specific systems (such as hurricanes) are tied to specific enhanced observations, the overall state of forecasting is still fairly poor.

There was widespread agreement that improved models, observations, and data assimilation systems (which allow the observations to correctly influence the model) have been responsible for the dramatic decrease in error for the short forecast (day 1) range. However, there are two distinct schools of thought regarding the lack of improvement in the medium range error growth rate. One view is that smaller scale convectively driven weather systems are not now and have never been handled correctly by the data assimilation procedures and the forecast models, so that the model in some sense "loses track" of the these weather systems. As these weather systems develop in different ways in the model and in nature over the forecast period, they force a continuous error growth. It is also likely that the current medium-range error growth rate represents the intrinsic limit imposed by baroclinic instability.

The second (more optimistic) point of view is that the current forecast models, with very high spatial resolution (40 - 80 km) and the ability to assimilate moisture-related variables, have in fact started to resolve and even to some extent predict the small-scale moisture dominated systems. Further improvement in the accuracy and resolution of models and data assimilation systems are thus likely to lead to improved predictions at both short and medium ranges. We can currently begin to resolve separate error growth rates for the day 1 and longer forecast ranges: the short time growth rates are larger. It seems that the models are starting to resolve the $k^{-5/3}$ portion of the spectrum, which is that range associated with less predictability in the standard turbulence theory. It seems that the reduced predictability (increased error growth rate) in the very short range has been more than offset by better models and data assimilation systems.

This raises the question of how to best make progress in the future: do we primarily need better models, better assimilation systems, or better observations? Dr. Hollingsworth emphatically answered this question with "Yes!" to all three. The dynamics and physics of latent heat release and the associated small scale circulations need to be better understood on a fundamental level. Advanced satellite observations and field experiments are clearly crucial. Translating this new knowledge into better models and data assimilation techniques will be required to make progress in actually predicting these systems. Whether there is a hard limit to predictability is an open question, but we have not reached it yet.

2.4 Tropical Predictability: Interactions with Moisture

Dr. Puri reviewed past work on tropical predictability in the context of suggestions made by Dr. Shukla more than 20 years ago: The upper limit of weather predictability in the tropics (in terms of forecast range) is much shorter than for mid-latitudes, because the amplitude of the tropical variability is smaller, and most of the day-to-day fluctuations in the tropics are determined by condensational-driven instabilities for which saturation occurs rapidly. Dr. Puri showed that short range forecasts of circulation anomalies have some skill in the tropics, although they have not shown improvement in recent years. However, the associated forecasts of precipitation, especially severe events, are generally poor and are given little credibility by forecasters. Even in the context of the large-scale monsoon circulation, models have problems in predicting the important temporal variations: onset, and active/inactive phase transitions. Tropical cyclone track prediction is one area in which significant success has been achieved and ensemble methods have shown the potential to provide useful information on track uncertainties. Although the overall results support Dr. Shukla's suggestion, the jury is still out: as in mid-latitudes, better observations in the tropics and data assimilation techniques, particularly the assimilation of rainfall rates, offer significant potential to make progress.

The role of the statistical equilibrium between moisture and dynamics was emphasized by Professor Emanuel. This important paradigm, which means revising notions of cause-and-effect (heating forces circulation, or vice-versa), caused a very lively discussion! A potent example is the successful forecasting of tropical cyclone intensity, using an atmosphere-ocean model with an equilibrium closure for moist heating. However, a counter-example was offered by Dr. Shukla in the context of the improvement in simulations of the monthly and seasonal circulation over North America made with observed sea surface temperatures. These improvements, achieved only with changes in the model "physics", especially the convective parameterization schemes, strongly support the notion that the sea surface temperature anomalies produce heating anomalies, which in turn force circulation anomalies.

Dr. Emanuel stressed that we still don't understand the subtle interactions between moist convection (clouds) and radiation, which may turn out to be important in capturing the propagation mechanism of large scale intra-seasonal oscillations in the tropics. Again, more fundamental understanding / observations are needed.

2.5 Grappling with Chaos: Forecasting Uncertainty

A major conceptual development in weather forecasting in recent years has been the emphasis on ensemble forecasts. The atmosphere's chaotic nature means that not only do small errors in the analysis grow rapidly to contaminate the forecast, but that the rate at which this happens is very dependent on the current atmospheric state. Dr. Toth described recent, moderately successful, efforts to use the probability distribution of ensemble forecasts to obtain a priori estimates of which forecasts will be good and which will not, that is to predict the predictability. Ongoing work to extract more information from the entire probability distribution of the ensembles, focusing initially on features such as bi-modality, appears to be very promising.

The deeper modeling implications of the chaotic dynamics of the atmosphere, and of the shallow ($k^{-5/3}$) spectrum on small synoptic scales were explored by Dr. Palmer. The concept of parameterization, by which the effects of very small-scale physical processes (e.g. convection, clouds) are described in terms of only mean values appropriate for the relatively coarse model grid, is called into question by the observed very shallow spectrum on sub-grid scales; at these scales there is robust variability that is not represented on the coarse grid. The fact that parameterization procedures only produce mean values and not a range of possible outcomes is likely to be responsible for the lack of realistic spread in forecast ensembles. This lack of variability may mean that the model is unlikely to sample the full non-linear distribution of observed states, with certain less frequently visited regimes being neglected altogether.

Introducing a probability distribution function (range of possible outcomes) for physical parameterizations may be done in a number of ways, from simply multiplying the parameterization output by a stochastic function to introducing a low-order dynamical model. Evidence that this improves the regime behavior of the atmosphere, including the Madden-Julian Oscillation (MJO), and of simple dynamical models is compelling.

3 Conclusions

3.1 The Known

- There has been steady progress in the large-scale accuracy of weather prediction in the last decade, and impressive progress in the last few years.
  - The improvement is especially large for the Southern Hemisphere
  - Analysis differences have become smaller
  - Improvement in the worst forecasts is considerable
- Forecast errors of the large scales have continued to decrease in the short range, primarily because the models are more accurate. Growth rates of the medium range forecast errors are unchanged from a decade ago. Most of the improvement in skill beyond day 1 of the forecast can be attributed to lower forecast error at day 1.
- Evidence for weather regimes is strong - and there is some evidence that transitions between regimes is associated with loss of predictability.
- Ensemble forecasts have enabled us to successfully quantify the uncertainty of forecasts. The possible prediction of observed bi-modality (regime behavior) by ensemble forecasts is promising.
- Ensemble methods and stochastic physics have helped to overcome some of the limitations of the parameterization paradigm, which are due to shallow small scale spectra. This helps even in the tropics.

- Reduction in large-scale errors, along with better high-resolution satellite sounding data, assimilation of cloud and rain information, and increased model resolution have made it possible to start to predict smaller scales successfully. There has been some success in predicting intense precipitation related to potential vorticity "wrap-up", tropical storm tracks, and even hurricane intensity.

- However, tropical weather prediction is in general in a poor state. Even the MJO cannot be maintained in most conventional models.

3.2 The Unknown

- The fundamental nature of the small-scale ($k^{-5/3}$) variability is still uncertain. It is not clear if the dynamics of small scale fluctuations are dominated by moist convection and gravity waves, in which case the classical turbulence-based error growth mechanism may not apply, or whether balanced rotational flow (and hence the classical error growth) plays some role. Yet there are no clear indications that further progress in prediction of the large scales will be impossible (it is likely that we have not yet hit the "wall").

  - The dynamics of the observed small synoptic scales which contribute to the shallow $k^{-5/3}$ spectrum are not well understood.

  - The role of moisture and convective latent heat release on these small scales is very important, and is only partially understood. The spectral approach of dry dynamics ignores this. In fact, spectra can be misleading, since structures which may not interact locally can give the appearance of interacting spectrally.

  - Fronts are small scale in one direction, large scale in the perpendicular direction. They are manifestly inhomogeneous and are poorly treated by the standard turbulence theory

- Some basics of tropical systems (e.g. MJO, small scale convective systems, and the interactions of radiation with clouds) are not well understood.

- A general conceptual understanding of the life cycles of error and error growth in the tropics is missing.

- The shallowness of the small scale spectra seems to indicate in a general way that the concept of parameterization is not well founded conceptually

- We do not know how much predictability can be improved by better simulation of weather regime behavior and in particular the transitions between regimes

3.3 The Unknowable

- The fundamental chaotic and non-linear nature of the atmosphere will impose some theoretical limit to our ability to forecast the fine details of the atmosphere's circulation at a specific location well in advance. As a result it is unknowable whether precipitation at a point will ever be predictable far in advance.

- It is unknowable whether we can ever assimilate the true structure of nature's water vapor field, given the intrinsically coarse resolution of satellite measurements.

- It is unknowable how far in advance we can predict the predictability, that is to what extent we will reliably know in advance that the forecasts for a given period are likely to be very good or very bad.

3.4 Future Directions

Our goals as a community should be to make better use of new observations, improve our understanding of moist physical processes and hence improve the numerical prediction models, and learn to make better probability forecasts. To achieve these goals, we need to:

- Place greater emphasis on the interactions between moisture, radiation and dynamics in our thinking

- Make further gains in model accuracy and resolution. A future generation of high resolution models, capable of assimilating, simulating and predicting meso-scale convective systems, may be essential for improving the skill of weather forecasts

- Create focused teams of experts

- Ensure access to enhanced computer power

- Call for continued international commitment to future observing systems; this is important not only for providing improved initial conditions but also for verification of model forecasts and validation of physical parameterizations

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A Workshop Participants

Jesse Ausubel	Sloan Foundation / Rockefeller University
Peter Bartello	McGill University
Lennart Bengtsson	Max Planck Institute, Hamburg
Tim DelSole	Center for Ocean-Land-Atmosphere Studies
Kerry Emanual	Massachusetts Institute of Technology
Ross Hoffman	Atmospheric and Environmental Researche
Anthony Hollingsworth	European Centre for Medium Range Weather Forecasting
Ben Kirtman	George Mason University / COLA
Doug Lilly	University of Oklahoma
Erik Lindborg	Kungl Tekniska Hogskolan, Stockholm
Ed Lorenz	Massachusetts Institute of Technology
Franco Molteni	International Centre for Theoretical Physics
Tim Palmer	European Centre for Medium-Range Weather Forecasting
W. R. Peltier	University of Toronto
Kamal Puri	Bureau of Meteorology Research Centre, Melbourne
Edwin Schneider	George Mason University / COLA
J. Shukla	George Mason University / COLA
David Straus	George Mason University / COLA
Zoltan Toth	National Centers for Environmental Prediction
Geoff Vallis	Geophysical Fluid Dynamics Laboratory / Princeton University

B Workshop Agenda

DAY 1: THE KNOWN		
8:30	9:00	Registration and Welcome
9:00	9:15	Introduction to Sloan Foundation Program *J. Ausubel*
9:15	9:30	Introduction to Workshop *J. Shukla, D. Straus*
Session 1: Historical Perspectives *(Chair: L. Bengtsson. Rapporteur: B. Kirtman)*		
9:30	10:05	A Perspective on the Limits of Predictability *E. Lorenz*
10:05	10:40	The Predictability of Two-Dimensional Turbulence - Early Studies *D. Lilly*
10:40	11:15	Predictability of Weather and Climate Based on Information Theory *T. Delsole*
11:15	11:35	(break)
Session 2: Quasi-Geostrophic Turbulence, **Small-Scale Spectra and Implications for Weather Predictability** *(Chair: D. Straus. Rapporteur: B. Kirtman)*		
11:35	12:10	Different Flavors of Turbulence *G. Vallis*
12:10	12:45	Modern Developments in QG Turbulence *P. Bartello*
12:45	2:00	(lunch)
2:00	2:35	Implications of Small Scale Spectra for Weather and Climate *T. Palmer*
2:35	3:10	Modern Observations of Small Scale Spectra and Energy/Enstrophy *E. Lindborg*
3:10	3:45	(break)
3:45	5:10	Summary and Synthesis of "The Known" *Discussion Leaders: T. Palmer, R. Pelier, D. Straus*

DAY 2: THE UNKNOWN		
Session 3: Current Limits of Weather Predictability: Are They Due to Models or Data? *(Chair: B. Kirtman. Rapporteur: D. Straus*		
8:50	9:35	Current Limits of Operational Weather Prediction
		A. Hollingsworth
9:35	10:10	What sets the current limits of predictability:
		Inadequate observations? Inadequate assimilation systems?
		Inadequate models?
		A. Hollingsworth
10:10	10:40	(break)
10:40	11:50	How Model-Dependent are Estimates of Weather Predictability?
		L. Bengtsson
11:15	11;50	(discussion)
11:50	1:15	(lunch)
Session 4: Enhancement of Predictability: Stationary Forcing and Weather Regimes *(Chair: R.Peltier. Rapporteur: D. Straus)*		
1:15	1:50	Existence and Predictability of Regimes
		F. Molteni, given by D. Straus
1:50	2:45	(discussion)
2:25	3:00	(break)
3:00	4:30	**Summary and Synthesis of "The Unknown"**
		Discussion leaders: L. Bengtsson, T. Hollingsworth, J. Shukla
Evening Session		
8:00	9:30	Informal Discussion of Predictability of Climate and Climate Change:
		(Preview of Sloan Climate Workshop)
		Discussion Leaders: E. Schneider, B. Kirtman

DAY 3: THE UNKNOWABLE		
Session 5: Predicting the Predictability: Interactions Between Moisture and Dynamics *(Chair: R. Hoffman. Rapporteur: J. Shukla*		
8:50	9:35	Current Limits of Operational Weather Prediction
		A. Hollingsworth
9:35	10:10	Short-Term Predictability Issues in the Tropics
		A. Puri
10:10	10:45	How Do Interactions Between Moisture and Dynamics Limit Predictability?
		The Optimistic and the Pessimistic View
		K. Emanuel
10;45	11;00	(break)
11:00	12:00	Summary and Synthesis of "The Unknowable"
		Discussion Leaders; K, Emanuel, K. Puri, B. Kirtman