Turbulence Forecasts for Manned and Unmanned Aerial Vehicles

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Aviation turbulence prediction - Motivation

- Turbulence has significant safety, economic and capacity impacts
  - In US, causes 75% of Part 121 accidents (OFCM Aviation weather Programs/projects 2004 update)
  - Structural damage
  - Economic cost of nearly $200 million per year (MCR Federal, 2003)
  - Second leading factor affecting the NAS (MOSAICATM/AvMET ARTCC/TRACON survey of wx factors impacting NAS)
Background – known turbulence sources

Clear-air Turbulence (CAT)

Mountain wave Turbulence (MWT)

Low level Terrain-induced Turbulence (LLT)

Cloud-induced or Convectively-induced Turbulence (CIT)

In-cloud turbulence

Convective boundary Layer turbulence

Turbulence forecasting procedure

- Aircraft turbulence ~ few meters to couple km
- Much smaller than present operational NWP model resolutions
- Cannot directly predict aircraft scale turbulence
- Only hope is to infer turbulence potential from larger resolved scales
  - Assumes downscale cascade of energy
  - Turbulence in mid-upper altitudes is in a stably-stratified environment where subgrid scale turbulence parameterizations do not work very well
- Multiple causes require multiple forecasting strategies

Graphical Turbulence Guidance Product (GTG)
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- Resolved scale “turbulence diagnostics” are automatically computed from standard weather model output (e.g., winds, temperature)

  \[ GTG = W_1D_1^* + W_2D_2^* + W_3D_3^* + \ldots \]

- R&D problems:
  - Develop Ds
  - Determine weights W based on comparisons to observations
  - Performance is NWP model dependent

- Calibration
  - Output is EDR (actually \( \epsilon^{1/3} \) m^{2/3} / s)
  - Rigorously tested against 100,000s of PIREPs and in situ EDR data
Some common turbulence diagnostics

- Frontogenesis function (good at upper levels)
  \[ F = \frac{D}{Dt} |\nabla \theta| \propto \frac{D}{Dt} \left| \frac{\partial \tilde{v}}{\partial \theta} \right| \text{ or } \frac{D}{Dt} \left| \frac{\partial \tilde{v}}{\partial p} \right| \]

- Unbalanced flow (Koch et al., McCann, Knox et al.)
  \[ R = -\nabla^2 \Phi + 2J(u, v) + f \zeta - \beta u \]

- Deformation X shear or speed
  \[ I = DEF |\tilde{v}|, \quad DEF = \left( D_{SH}^2 + D_{ST}^2 \right)^{1/2} \]
  \[ D_{SH} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}, \quad D_{ST} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \]

- Eddy dissipation rate \( (\varepsilon^{1/3}) \) computed from second order structure functions of velocity and/or temperature
  \[ D_q(s) = \langle [q(x) - q(x + s)]^2 \rangle \]
  \[ D_q(s) \propto C_q(s) \varepsilon^{2/3} D_{REF}(s) \approx C_q(s) \varepsilon^{2/3} s^{2/3} \]
Calibration of GTG using in situ edr from commercial aircraft

• Background
  – Provides atmospheric turbulence metric: eddy dissipation rate (edr), actually $\varepsilon^{1/3} (m^{2/3}/s)$
  – Records peak and mean
    • UAL every minute
    • Algorithm updated to event-based recording + heartbeat
  – Avoids uncertainties in PIREPs (intensity, location, time)

• Status
  – ~100 UAL 757s
  – ~ 70 DAL 737-800s
  – Expect ~ 340 SWA 737-700s by end of summer

• Future
  – UAL, DAL 767s
  – UAL 777s with Boeing?
  – AIRTRAN?
GTG = Weighted ensemble of turbulence diagnostics

0 h forecast valid at 22 Sep 2006 15Z
Current GTG3 RUC-based performance (6-hr fcst ROC curves 12 mos. valid18Z) – Discrimination of smooth vs. moderate-or-greater (MOG)

AUC = 0.812

GTG3

Null-MOG
GTG3
AUC = 0.812

Individual diagnostics

High threshold
(Predict no turb)

Low threshold
(Predict turb everywhere)
GTG status

- GTG2 uses RUC 20 km grids
  - 10,000 ft MSL-FL460
  - CAT only
  - Available on ADDS: http://aviationweather.gov/adds

- WRF-based systems
  - Operational over Taiwan (CAA)
  - Climatologies at the French Navy: CLIMOPS system.
    - All altitudes: sfc-FL460
  - WRF-RR will replace RUC-based system late CY10.

UAV applications?
CLIMOPS

Global reanalysis
Meteorol. observations

WRF model

GTG

Year 1

Global reanalysis
Meteorol. observations

WRF model

GTG

Year 2

...
...
...

Year ...

Global reanalysis
Meteorol. observations

WRF model

GTG

Year N

Analysis

Variability

NCAR
Use of indices as ensembles provides probabilistic output

GTG

Std dev

Prob of smooth

Prob > light

Prob > mod

Prob > severe

0 h forecast valid at 22 Sep 2006 15Z
GTG Calibration for CLIMOPS

- GTG Calibration requires PIREPS, only available over CONUS
- GTG Calibration is model dependant. Calibration must be done with same configuration than climatology -> $\Delta x = 3.3$km

- Create WRF outputs over CONUS at 3.3km grid increment 2 days (1st & 15th) of each month of 2006.
- 700 hours of CPU per day of simulation, 25,200 CPU hours all together.
WRF CONUS RUNS

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CONUS RUNS

CONUS WRF domains configuration (left) and temperature cross section (right)
WRF CONUS RUNS

Horizontal temperature perturbation East-West cross section. Terrain has been smoothed on right panel.
WRF CONUS RUNS

Horizontal vertical velocity (left) and temperature perturbation (right)
East-West cross section.
Current GTG work areas

- Probabilities of MOG, SOG
- Explicit MWT, CIT diagnoses
- Low-level turbulence forecasts (< 10,000 MSL)
- GTG-N
- GFS-based Global GTG (NASA-sponsored)

GFS GTG 12-hr fcst, magenta=cloud tops>35,000 ft, AIREPs, in situ turbulence measurements from Delta, United and Qantas aircraft, ± 90 min (blue = null, light, orange = moderate, red severe turbulence)
Application to UAV testing

• GTG technique can be used to provide forecasts of EDR
  – Can use operational NWP models
  – Site-specific mesoscale model
  – Either requires assumption of downscale cascade

• Must calibrate EDR (atmospheric metric) to UAV loads
  – Table driven approach using response function of UAV
  – Using actual UAV recorded flight data