Estimation of Optical Turbulence Using Multiscale Atmospheric Models
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Introduction

Optical Turbulence (O.T.)
- The wave phase and amplitude of the optical and electromagnetic waves are highly affected by the small-scale variation of temperature and specific humidity.
- The turbulent atmosphere causes the intensity of a light beam to fluctuate or scintillate, causes beam to wander, and causes the distortion and random displacement of images. (Hutt, 1999)

Fig. 1 A laser beam propagating through the atmosphere spreads due to diffraction but is also influenced by turbulence in the form of randomly varying eddies. (Burger et al., 2008)

Fig. 2 Double star Zeta Aquarii (which has a separation of 2 arcseconds) is blurred by atmospheric turbulence. (Image Courtesy: Alan Adler)

Applications
- Estimation and prediction of optical turbulence are significant to a wide range of applications: environmental monitoring, optical communication, astronomy, sensing with detection, reconnaissance and identification, guiding systems or directed-energy systems. (See Cheinet et al., 2010 and the references therein)

Refractive index structure parameter
- Under some approximations, the optical turbulence effects can be quantified in terms of structure parameter (Cn2) of refractive index (n) (units m-2/3). (Tatarski 1961)

Estimation Cn2 using meteorological models
- The small-scale turbulence is primarily driven by the meteorological forcings including synoptic-scale variability, diurnal cycles, large-scale gravity waves, convective plumes, and mesoscale circulations etc.
- Cn2 is chosen to describe the effect of the optical turbulence. It depends on temperature structure parameter C10, if the minor wavelength and humidity dependence are ignored.
- Numerical meteorological models can be utilized to estimate Cn2 from temperature and turbulent variables.

\[
C_n^2 = \left( \frac{n(\mathbf{p}) - n(\mathbf{p}_0)}{p_0} \right)^2 / |\mathbf{p} - \mathbf{p}_0|^2 / 3
\]

Direct Cn2 and C10 Calculations
- Monin-Obukhov similarity functions
  \[
  f_i \left( \frac{z}{L} \right) = f_i \left( \frac{z}{L} \right) \text{ Stability parameter (z/L)}
  \]

Stably Stratified Surface Layer

\[
f_i \left( \frac{z}{L} \right) = \frac{1}{1 + \left( \frac{z}{L} \right)^{\frac{1}{2}}}
\]

MOST 2. Thiriamann-Grasal (1992)
\[
f_i \left( \frac{z}{L} \right) = 6 \left( \frac{z}{L} \right) + 7 \left( \frac{z}{L} \right)^{1.3}
\]

MOST 3. Krik (Hartogensis, 2006)
\[
f_i = 5.5 \text{ for } \frac{z}{L} < 0.1
\]

\[
f_i = 5.5 \left( \frac{0.1}{L} \right)^{0.4} \text{ otherwise}
\]

Regression model function
Sadot et al. (1992)
\[
C_n^2 = \frac{a_1 W + b_1 T + c_1 R H + c_2 R H^2 + c_3 R H^3 + d_1 W S + d_2 W S^2 + d_3 W S^3 + d_4 W S^4 + e}{W \text{ is temporal hour-wise, } T \text{ is temperature, } R_b \text{ is relative humidity, } a, b, c, d, e \text{ are numerical regression coefficients.}}
\]

Optical turbulence data from a coastal site will be analyzed and simulated (field experiment at Beauford, NC currently ongoing).

New MOST function will be developed from the LES and observational databases.

Case Study: CASES-99

October 23-25, 1999
- The first night was intermittently turbulent, with several turbulent mixing events (Sun et al. 2003a). A low-level jet (LLJ) event occurred during the mean wind speed of 7.6 m s-1. The Height of the LLJ was approximately 100 m.
- In the second (turbulent) night, a continuous LLJ with mean wind speed of 15.2 m s-1 was observed.
- The LLJ height was approximately 200 m and it increased throughout the night.

Fig. 4 Surface analysis at 0 UTC (top) and 12 UTC (bottom) on October 24, 1999. The Midwest of the U.S. was dominated by a synoptic-scale surface high pressure system.

Observations
- A diverse suite of observational datasets were utilized for model validation. These datasets were collected by a Doppler lidar, a small-aperture scintillometer, sonic anemometers, and a sounding system etc.

Fig. 5 Pictures of observation instruments: sounding (left), tower (middle), and sonic anemometer (right).

Model Configuration

WRF
- Model:                   WRF v3.3
- Initial condition:      NARR
- Grid size:              27/9/1 km
- PBL scheme:            RRTMG
- Ra scheme:              WSM 5-class
- MP scheme:             Kain-Fritsch (d1 and d2)
- CP scheme:              obs_coff, obs_rinxy, obs_rinsig, obs_twinds

LES
- Domain size:           800 m x 800 m x 790 m
- Time:                  05z-12z Oct. 24th
- Grid size:             10 m

Data Assimilation:
- U, V, and T: NCEP ADP Global Surface Observational Data
- Weather Data:           obs_coff, obs_rinxy, obs_rinsig, obs_twinds
- = 6.6-4 s-1, (1/10 min)
- 270/90/30/10 km
- 0.002 (eta)
- 10 min = means +/- 10 min around observation

Results
- The WRF model simulated a weaker and slightly higher LLJ due to the enhanced diffusion.
- The modeled LLJs were 3 hours delayed comparing with the observed.
- The LES model simulated a stronger jet and slightly jet higher due to lack of subsidence.
- WRF and LES captured the wind direction and potential temperature profiles remarkably well.
- WRF and LES did not show the intermittency in surface fluxes during nighttime.

Future Work
- Cn2 will be calculated directly from the temperature structure function using LES – generated flow fields output:
  \[
  \langle T(x + r) - T(x) \rangle^2 \rangle \sim C_n^2\langle r \rangle^{2/3}
  \]

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Selected References