Prospects for wind lidar assimilation

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ECMWF seminar: Use of satellite observations in NWP

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Outline

1. Importance of wind for NWP
2. Doppler wind lidar
3. The Aeolus DWL mission
4. Expectations for Aeolus NWP impact
Importance of wind observations for NWP

- **Extratropics:**
  - Geostrophic adjustment theory

- **Tropics:**
  - Wind more efficient at recovering equatorial waves than mass (e.g. Žagar et al. 2004)

- Wind from model dynamical adjustment (4D-Var) to other variables important too
  - Mass sampled in time (e.g. Talagrand 1981)
  - Humidity tracer advection (e.g. Peubey and McNally 2009)
  - But wind more efficiently determined with direct wind obs
How accurate are global wind analyses?

- e.g. 300 hPa wind speed RMS difference between GFS and ECMWF
- Largest uncertainties in poorly observed areas

Langland and Maue (2012)

Similar structures in ECMWF Ensemble of Data Assimilation (EDA) spread, 12-h FC 300 hPa zonal wind, mean Jan-Sep 2014
Winds assimilated in an ECMWF cycle

- Very uneven distribution
- AMV coverage good in tropics, but obs errors large
- Stratosphere poorly sampled

$\log_{10}(\text{number obs per area})$
- Any hope for filling the gaps?
- Aeolus Doppler wind lidar (DWL) should help the vertical sampling:
  - ESA Earth Explorer Core Mission, chosen in 1999
  - Technology demonstration, ~3 years
  - Will be first European lidar and first wind lidar in space
  - Launch 2016
    - Long delays due to technical difficulties, but now on track
Doppler wind lidar

- DWL measures Doppler frequency shift of backscattered light

\[ \Delta f = 2f_0 v_{LOS}/c \]

- Scattering from:
  - air molecules (clear air) and particles (aerosol/cloud)
  - **Wind** = Average molecules/particle movement in volume of air
Clear air winds: Rayleigh scattering

- $I \propto \lambda^{-4}$; scatterer size $< \frac{\lambda}{10}$, air molecules $\rightarrow$ ultra-violet

- Thermal motion $\rightarrow$ Doppler broadening
  - e.g. 459 m/s for $T=15$ °C
  - Brillouin scattering effect due to acoustic waves (at high pressure) has to be considered

- **Wind** measured as shift in mean of distribution

\[
\sigma_v = \frac{2}{\lambda} \sqrt{\frac{kT}{m}}
\]

Rayleigh (Gaussian)
Rayleigh-Brillouin

\[
\Delta f \text{ (GHz)}
\]
Cloud/aerosol winds: Mie scattering

- Particle sizes > \( \lambda \); intensity not strongly \( \lambda \) dependent
- Doppler broadening negligible (particles heavy)
  - Narrow spectrum
  - No \( T, p \) dependence
- Wind measured as shift in mean of sharp Mie peak

Rayleigh-Brillouin
Rayleigh-Brillouin+Mie peak
**DWL features**

- **Advantages:**
  - High resolution and accuracy possible
  - Measurement closely linked to wind

- **Disadvantages:**
  - No transmission through thick cloud
  - Space-borne DWL limitations:
    - Complex technology (but ground/air based works fine!)
    - Obtaining vector wind not easy
    - Limited sampling across-track (e.g. sub-satellite “curtain”) from one satellite
    - Low signals at ~400 km range
Aeolus DWL

12 hrs coverage, ~72K “good” winds; ~11% increase in wind GOS

 Mostly zonal component of wind
Coverage up to 83 °N/S

Example of Aeolus vertical sampling

Rayleigh

Mie

Continuous coverage along-track
What might Aeolus winds look like?
Example simulator input: $\log_{10}(\text{scattering ratio})$ at 355 nm (derived from CALIPSO)

$$\rho = \frac{\beta_m + \beta_p}{\beta_m}$$

CALIPSO scene courtesy of G. J. Marseille and J de Kloe, KNMI
Simulator input: “True”
HLOS wind (ECMWF)

Output: Level-2B processed “clear-Rayleigh” HLOS wind i.e. what the winds should look like
Simulator input: “True” HLOS wind (ECMWF)

Output: Level-2B processed “cloudy-Mie” HLOS wind
Simulated L2B HLOS wind error statistics

Rayleigh-clear

2-3 m/s
Typically < 0.5 m/s

Mie-cloudy

1-2 m/s
~0.3 m/s

Rayleigh and Mie are complementary

Mean(error)
Stdev(error)
Number of obs
ESA required accuracy

10/09/2014 wind lidar assimilation
Error sources for Aeolus HLOS winds

● Instrument errors:
  - e.g. readout noise, dark-current noise, laser frequency stability
  - Pointing/spectrometer alignment errors
    ▪ improved by ground returns (zero wind reference)

● Unwanted signals:
  - Aeolus measures photon counts from interferometers.
    ▪ Shot noise: SNR ~√N, main error source
  - Solar background light
  - Sampling error: wind/backscatter variability
  - Vertical wind
  - Rayleigh winds \( f(T, p) \) of atmosphere

● Errors during calibration lead to systematic errors
Acceptable noise levels through averaging

Laser pulses (pulse rate 50 Hz, energy 80-120 mJ)

- Ground track velocity ~7.2 km/s
- Measurement = accumulation of 20 pulses on instrument
- Observation = average of e.g. 30 measurements, in ground processing
Aircraft winds every 1 km

What Aeolus Rayleigh winds might observe
Wind error vs. averaging length

- Comparing L2B winds to “point-wind” from ECMWF T1279 model
- Can achieve better accuracy at small scales with Mie compared to Rayleigh
What to assimilate for Aeolus?

More complex obs operator: increasing knowledge of instrument/physics needed

\[ H(x) \]

Current choice

L2B HLOS wind: Mie Rayleigh

HLOS wind \( H(u,v) \)

2D-HLOS wind \( H(u,v) \)

Wind vector \( H(u) + H(v) \)

Geophysical variable/direct obs

Need a priori: \( T, p \)

Need a priori: e.g. 1D-Var retrieval

"Raw" obs

Photon count \( H(u,v,T,p,CLWC,CIWC, \text{aerosol}) \)

Rayleigh Response (RR)

Rayleigh Response (RR)

"Raw" obs

Photon count

Photon count

More complex retrieval (processing)
Aeolus winds for NWP: L2B

- Level-2B processor* provides
  - Retrieval of HLOS winds
    - Geolocated – geometric height, lat, lon, azimuth angle, time
    - Error estimates for each wind, quality flags
  - Flexible classification into wind types – cloudy or clear (currently)
  - Flexible horizontal averaging of spectrometer counts
    - Some control of noise and representativity of observations
  - Rayleigh winds corrected for temperature, pressure and Mie cross-talk
  - In future: estimates of optical properties
  - Many processing options controllable from settings file

- Research mission; encourage users to play with L2B processor

* developed by ECMWF, KNMI, Météo-France, DLR. See e.g. Tan et al. (2007)
Expectations for Aeolus NWP impact

Recent assessments relevant to Aeolus:

1. EDA spread experiments using ECMWF model
   

2. Recent OSSE with DWL (Zaizhong et al., 2013) by JCSDA

3. ECMWF OSEs using available in situ wind observations

1. and 3. were financially supported by ESA
Aeolus EDA experiments

- Reduction in ensemble spread → positive impact
- Accurately simulated Aeolus obs
- ECMWF, T399 (wind impact for small-scales could be underestimated)
- Impact similar to radiosonde network:
  - Largest at ~200 hPa, tropical oceans and winter poles
  - ~5% improvement short-range – could lead to 1-3 hrs impact

Image courtesy of ESA VHAMP project
Impact on tropical winds; 15% reduction in RMSE (1-look), short-range at 200 hPa, but lost after 5 days (NCEP system?)

- NCEP GSI/GFS system, 2009
- Different DWL satellite configurations tested

NH impact 500 hPa Z:
- 4-look DWL, ~5 hrs
- 1-look DWL, ~1 hr

SH impact 500 hPa Z:
- 4-look DWL, ~6 hrs
- 1-look DWL, ~3 hrs
HLOS impact in ECMWF system
by A. Horányi, C. Cardinali, M. Rennie and L. Isaksen (QJRMS, 2014)

- OSEs using *in situ* observations:
  - aircraft; radiosondes; PILOT and wind profilers

- Assessed impact of assimilation of HLOS winds
  - convert \((u, v)\) → HLOS wind
  - can real single-component wind obs give useful impact?
    - Yes, ~70% impact of vector wind
  - Typical impact of zonal HLOS: 2-5 hrs in NH extratropics
  - Large impacts in tropics despite very few obs

Decrease of error in total energy of the 24h forecast error
Finally: *Tentative* expected impact for Aeolus

- *If* mission error specifications are met:
  - Extratropics:
    - 500 hPa geopotential: ~3 hrs, SH, 2-5% analysis improvement:
      - Difficult for any one observation type to show “large” impact on top of full OS
    - Expect similar impact for wind
  - Tropics:
    - Evidence of locally large impacts, e.g. up to 15% improvements in upper tropospheric winds
  - But the proof of the pudding is ...
Thanks for listening. Any questions?

Aeolus L2B processing software available to download:
http://www.ecmwf.int/en/research/projects/aeolus