A new observation operator for the variational assimilation of equivalent neutral scatterometer ocean surface wind vectors

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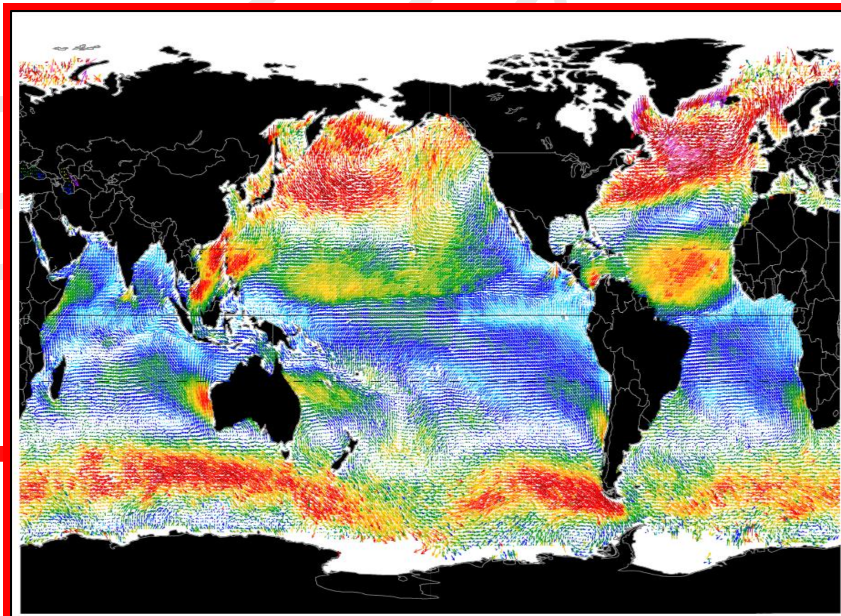

Canadian Meteorological Center

April 8th 2011

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RECHERCHE ET SAUVETAGE SEARCH AND RESCUE

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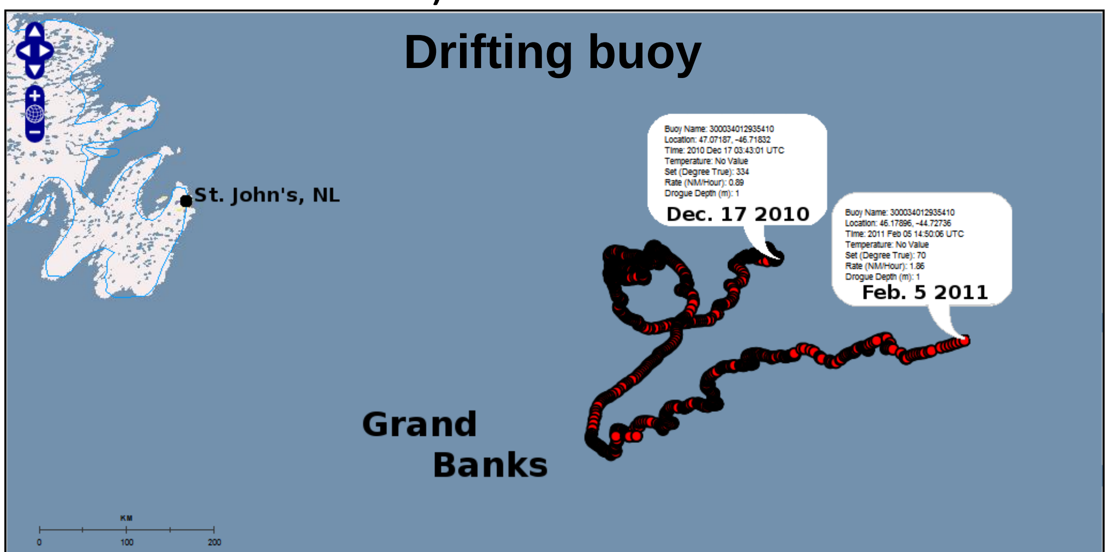
Outline

- Overall **context** of research
  - **S**earch **A**nd **R**escue-**N**ew **I**nitiative **F**unds **(SAR-NIF) funded** project
  - Specific **goals**
- **Background** on:
  - **Scatterometry** vs. **ocean surface winds**: Not really a real wind!!
- Improvements to **scatterometer wind data assimilation**
  - Surface wind variational **data assimilation**: **concepts**
  - New **observation operator** and its **impact**
- **GEM** short-term forecasts vs **scatterometer** comparisons [i.e. **O-F**]
  - What are they telling us about the model wind (stress)…

Context – SAR-NIF project

- **Env. Can**. and **Dept. of Fisheries & Oceans** (DFO) partnership
- **Coordinated research** & **development** efforts toward:
  - Improved **NWP ocean surface wind** analyses & forecasts } ARMA CMDA
  - ↓
  - Improved ocean **surface currents**
  - ↓
  - Improved estimates of **drift of "objects" at sea** (search & rescue missions)

  } DFO



Context – SAR-NIF project

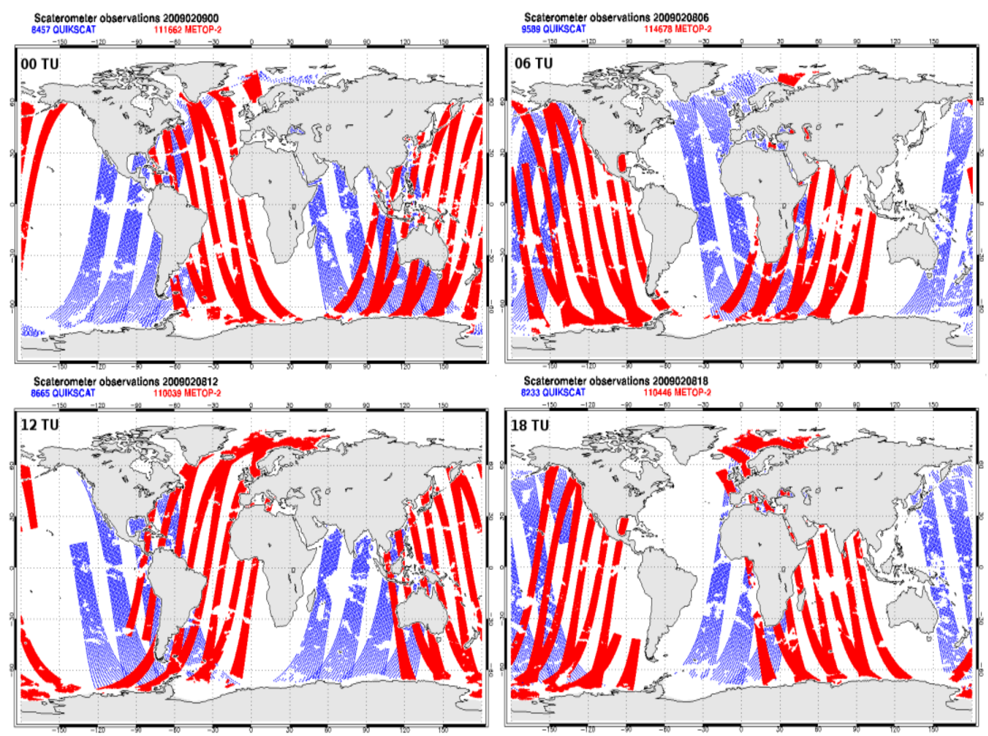
- **Improving NWP ocean surface wind** analyses & forecasts:
  - Operational implementation of Advanced SCATterometer **(ASCAT) wind** observations (completed in March 2009)
  - Improved **quality control** and **thinning** of observations + **optimized observation error statistics** (upcoming seminar by Mateusz Reszka)
  - **Model-to-observation** correspondence (nonlinear **observation operator**) & associated **tangent linear + adjoint** (TL/AD) for improved scatterometer wind data assimilation

↳ Work performed in the context of the **Global Deterministic Prediction System** (GDPS) but developments **transferable to other systems**

Context – Usage of scatterometer winds

- Operationally assimilated in:
  - Global **4D-var** deterministic & **EnKF** ensemble forecast systems
  - Regional **3D-var** deterministic system

- Observations:
  - SeaWinds (on QuikSCAT) **100-km** winds
    - Assimilated from **May 2008** to **23 Nov. 2009 (sensor failure)**
  - ASCAT (on Metop-A) **25-km** winds
    - **Thinned** to ~100 km
    - Assimilated since **March 31 2009…**



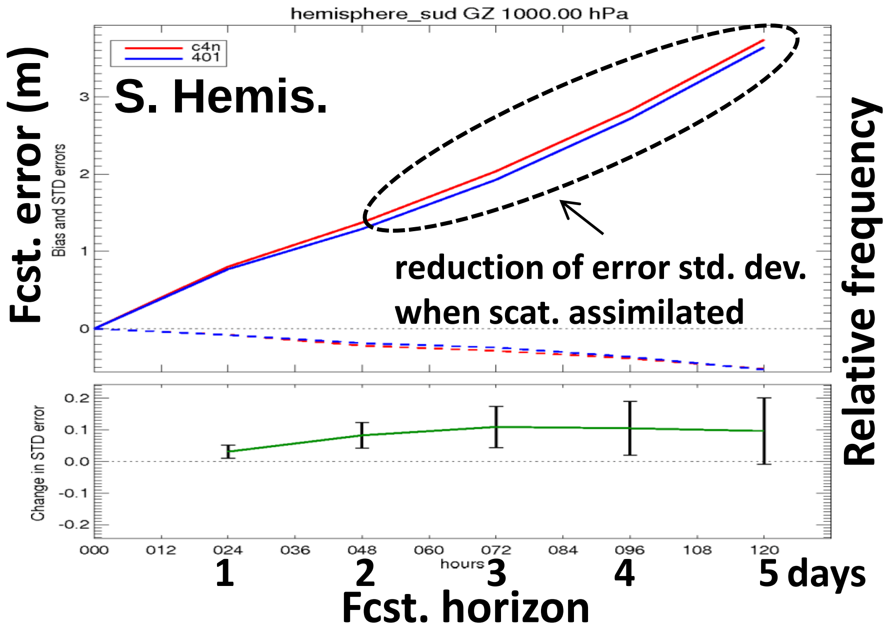
Context- Impact of scatterometer winds

- **Positive impact** on atmospheric forecasts in **S. Hemis.**

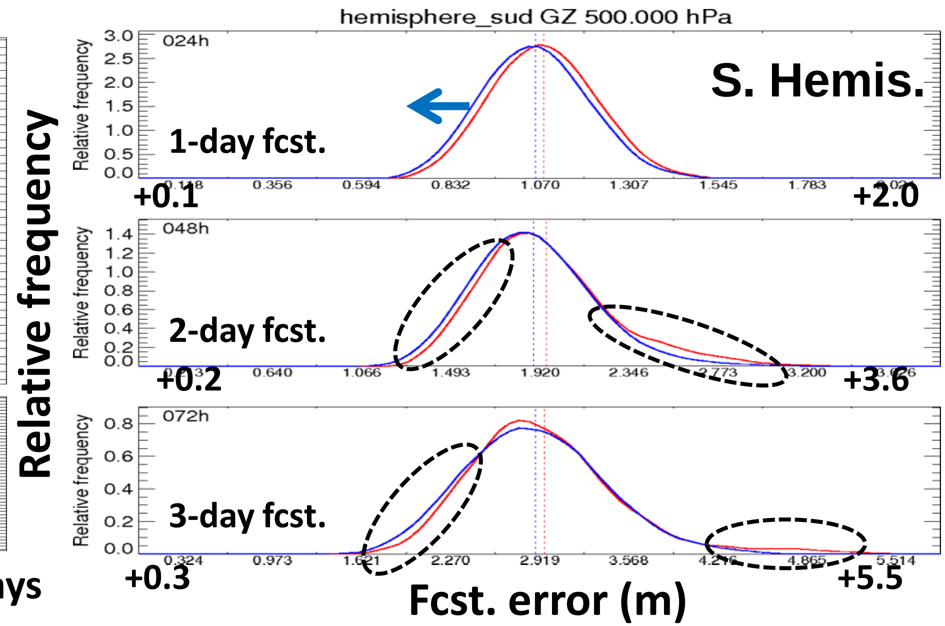
Verification against 4D-var analyses (January 2009)

without scat.
with scat. (SeaWinds+ASCAT)

Geopotential @ 1000 hPa



Geopotential @ 500 hPa

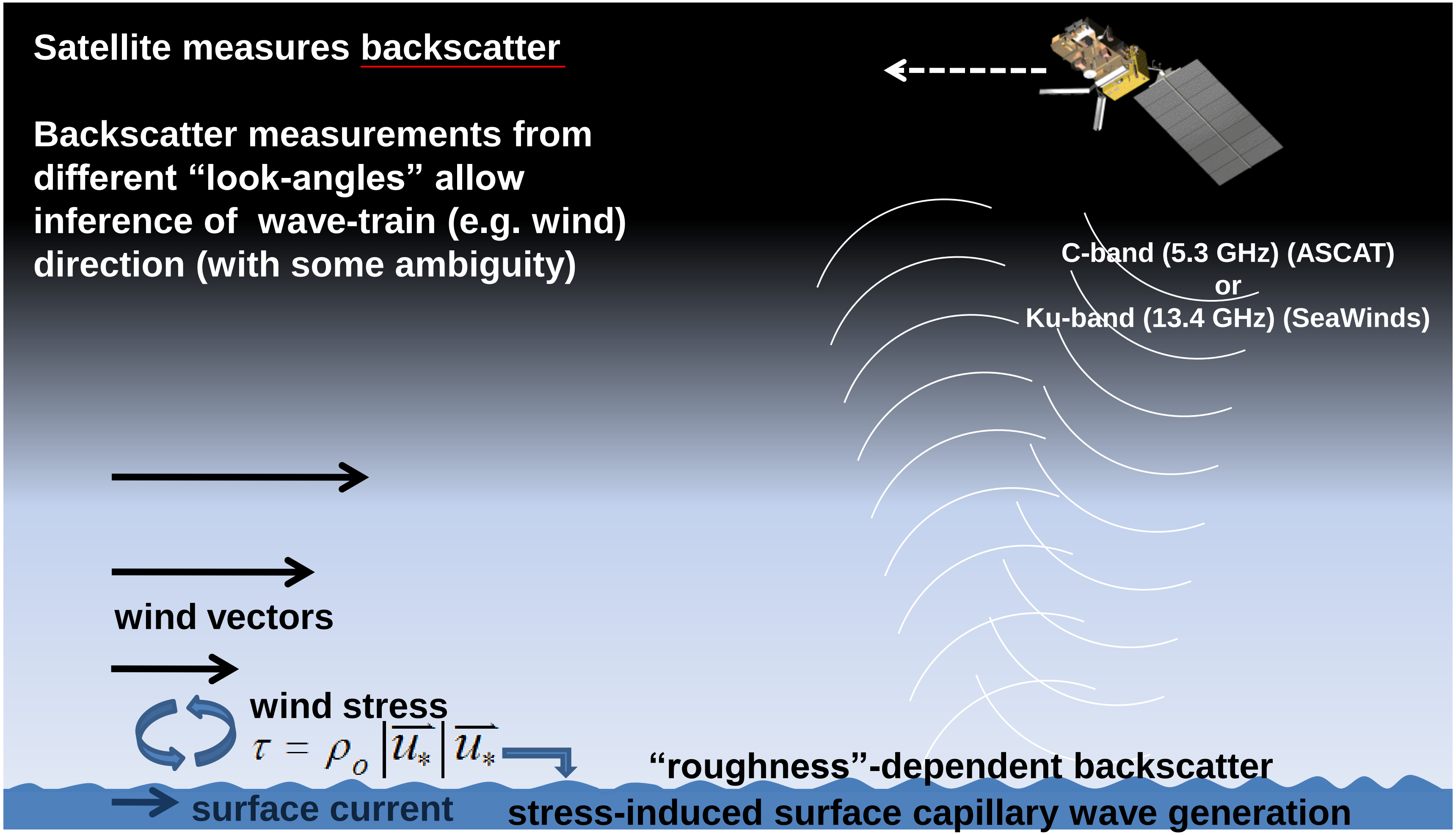


Part 2

Background on scatterometry

Scatterometry & ocean surface winds

- **The physics underlying the observations**



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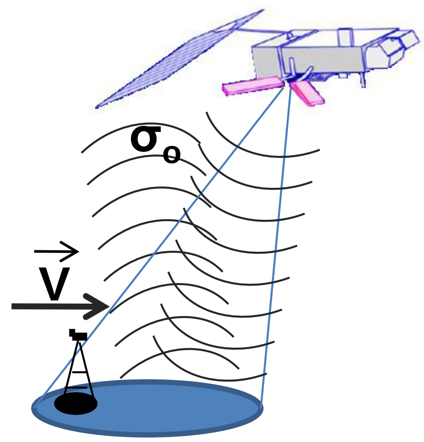
Scatterometer wind retrievals

- **Wind retrievals** (provided by **Royal Netherlands Meteorological Institute – KNMI)**

→ **Backscatter** (σ_o) to **wind vector**

→ Empirical **G**eophysical **M**odel **F**unction (**GMF**)

→ Derived from **collocated** radar **backscatter** and **buoy observations**



→ Retrievals calibrated as **10-m equivalent neutral** winds

Equivalent neutral wind

- **Real (stability-dependent)** wind profile

$$\begin{bmatrix} U(z) \\ V(z) \end{bmatrix} = \frac{u_*}{k}\left[\underbrace{\ln\left(z/z_o+1\right)}_{\text{log wind profile}} + \underbrace{\psi_m\left(\left(z+z_o\right)/L\right) - \psi_m\left(z_o/L\right)}_{\text{"Stability modification" to log profile}}\right]\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$$

- **Equivalent neutral** wind profile

$$\begin{bmatrix} U_{en}(z) \\ V_{en}(z) \end{bmatrix} = \frac{u_*}{k}\left[\ln\left(z/z_o+1\right)\right]\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$$

→ Relation with **wind stress:** $\tau = \rho_o \left|\overrightarrow{u_*}\right| \overrightarrow{u_*}$

Equivalent neutral wind

- **Equivalent neutral wind profile**

$$\begin{bmatrix} U_{en}(z) \\ V_{en}(z) \end{bmatrix} = \frac{u_*}{k}\left[\ln\left(z/z_o + 1\right)\right]\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$$

Friction velocity:

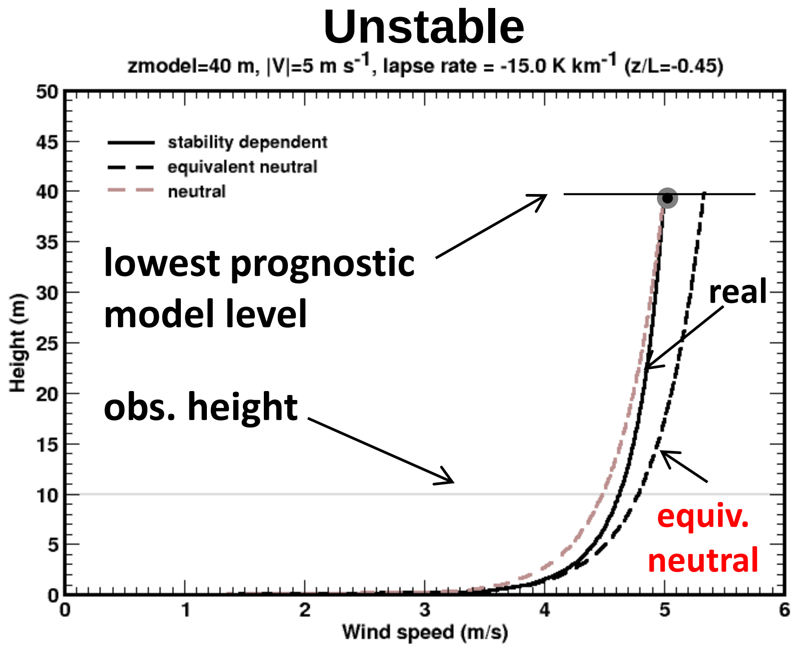
$$u_* = \frac{k\sqrt{(U(z))^2 + (V(z))^2}}{\left[\ln\left(\frac{z}{z_o}+1\right) + \psi_m\left(\frac{z+z_o}{L}\right) - \psi_m\left(\frac{z_o}{L}\right)\right]}$$

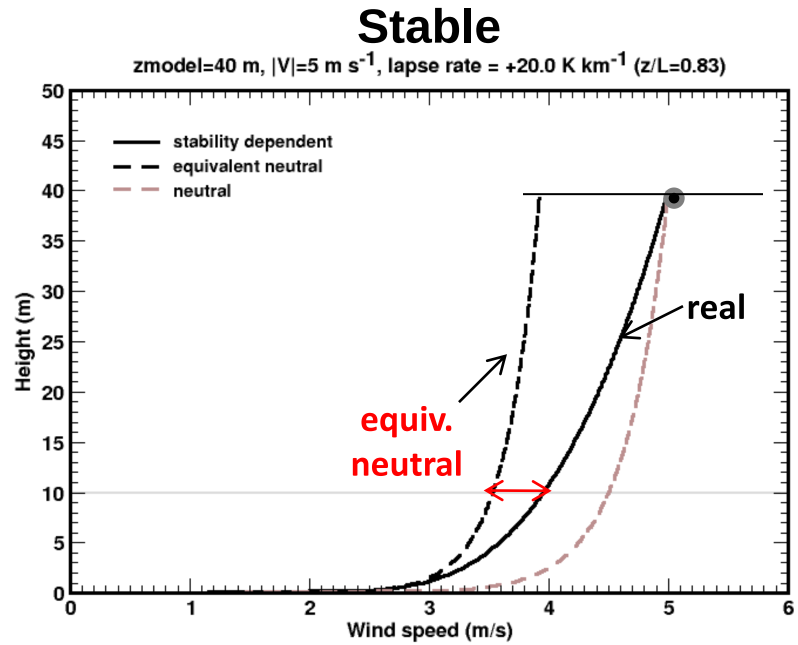
Ocean surface roughness length:

$$z_0 = C_{ch}\frac{u_*^2}{g} \qquad C_{ch} = 0.018$$

Equivalent neutral wind

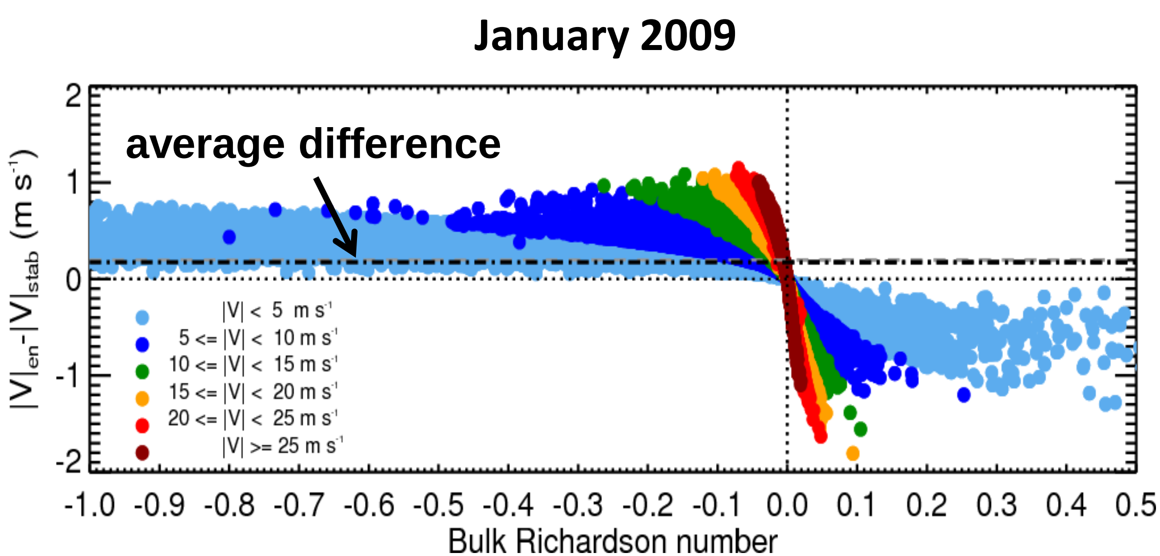
- **Stability-dependent or "real" vs. equivalent neutral wind profiles**





Equivalent neutral wind

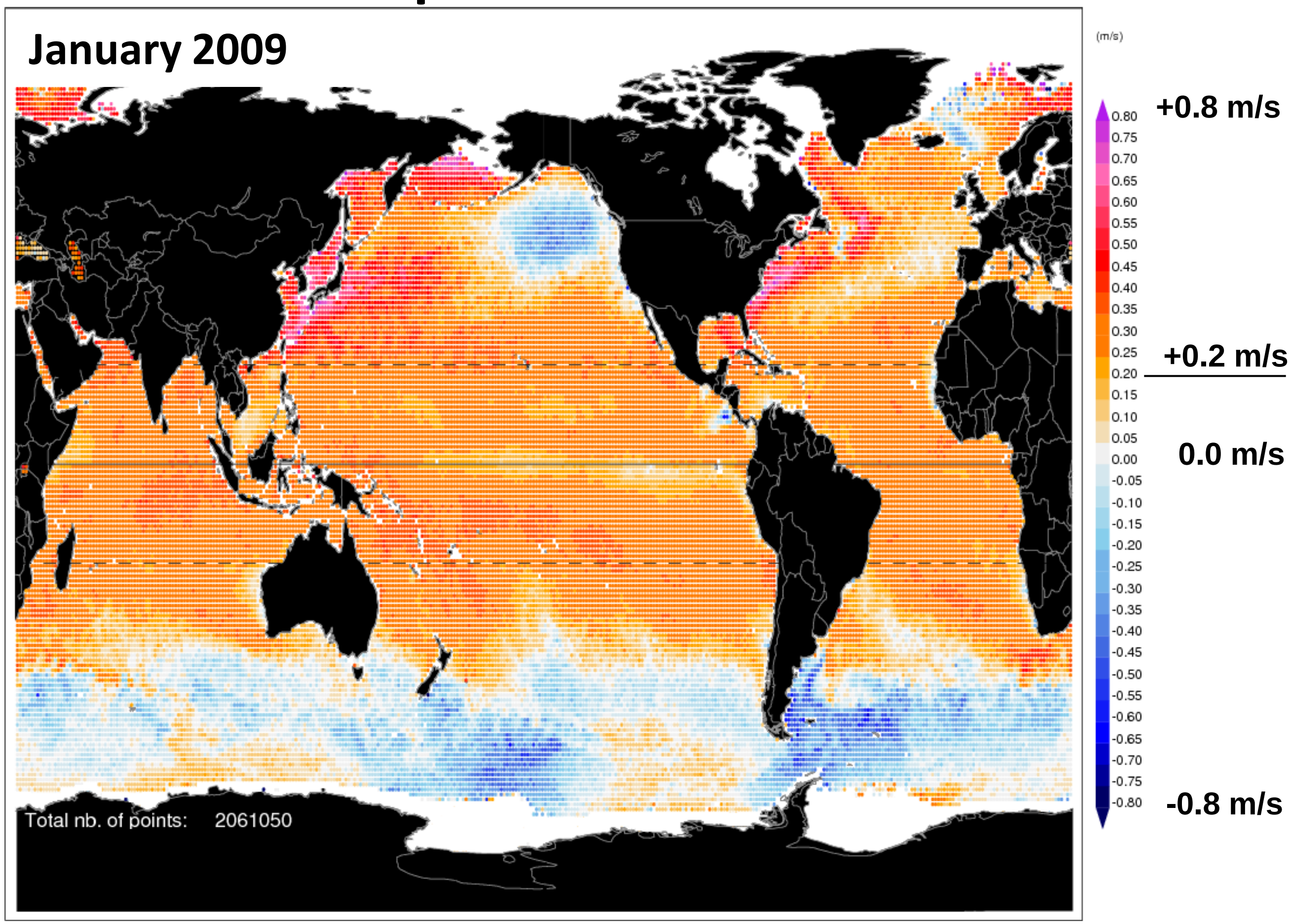
- **Difference between equivalent neutral & stability-dependent 10-m wind speed**
- **Average difference ≈ +0.2 m s^{-1}**
- **In accord with Portabella & Stoffelen (JAOT,09) Kara et al. (JGR, 98)**



- **But:**
  - Dependence on surface layer **stratification**
  - Dependence on **wind speed**

Equivalent neutral wind

- **Difference between equivalent neutral & stability-dependent 10-m wind speed**



Part 3

Improvements to scatterometer wind data assimilation

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Equivalent neutral observation operator

Scatterometer wind data assimilation: concepts

- **Variational data assimilation: cost function** to minimize (**incremental** formulation)

$$J(\delta\mathbf{x}) = \underbrace{\frac{1}{2}\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x}}_{J_b} + \underbrace{\frac{1}{2}(\mathbf{H}\delta\mathbf{x}-\mathbf{d})^T\mathbf{R}^{-1}(\mathbf{H}\delta\mathbf{x}-\mathbf{d})}_{J_o}$$

Increment:

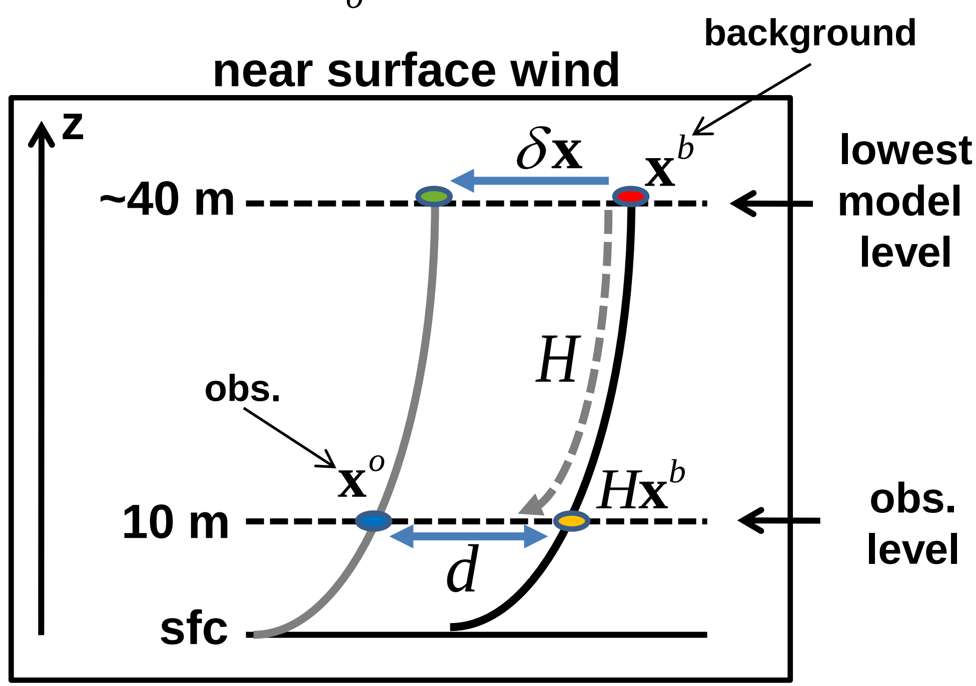
$$\delta\mathbf{x} = \mathbf{x} - \mathbf{x}^b$$

Innovation:

$$\mathbf{d} = \mathbf{x}^o - H\mathbf{x}^b$$

$\mathbf{x}^o$ → **Obs.**; $\mathbf{x}^b$ → **background**; H → **NL obs. operator**

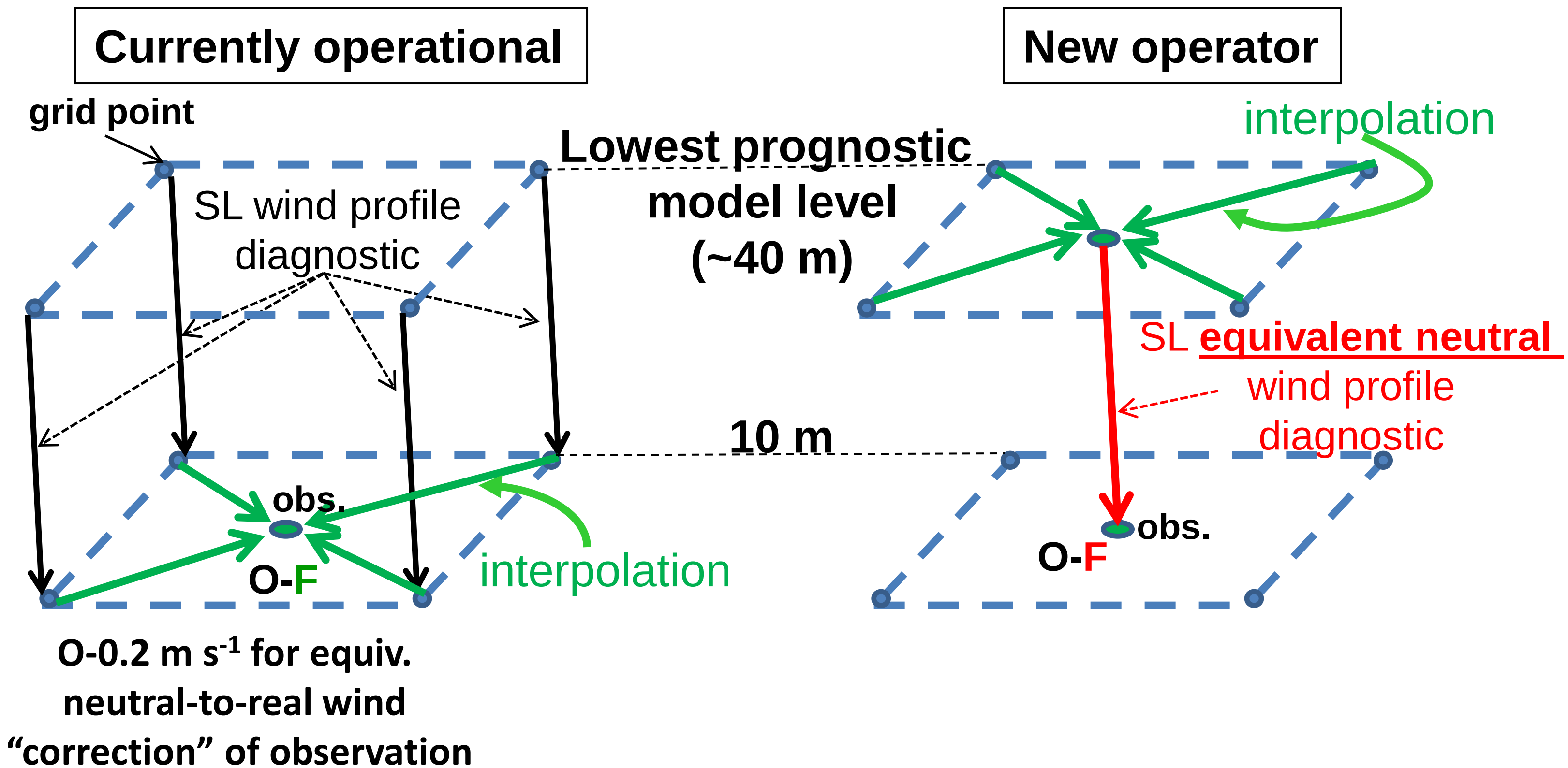
Tangent linear of H **:** $\mathbf{H}$



Observation operator – forward

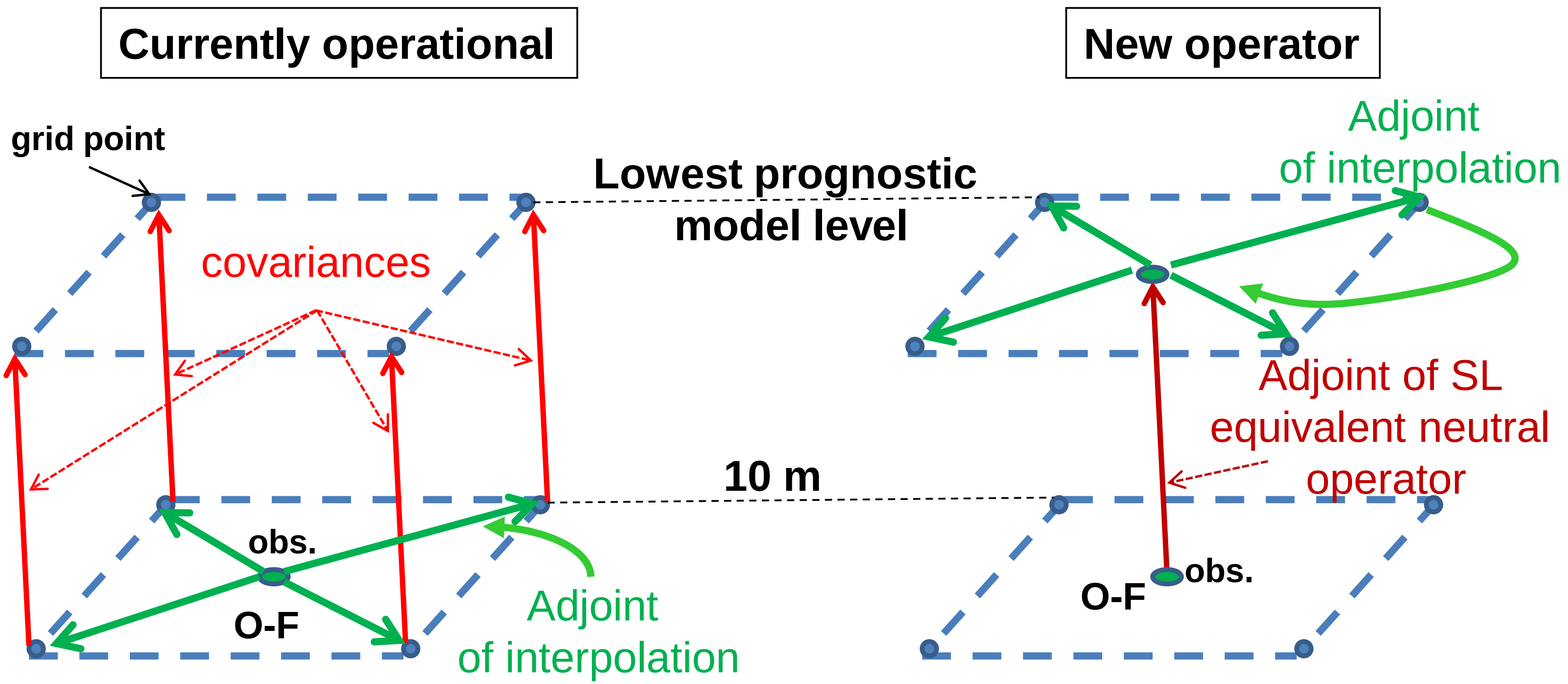
- **Model-to-obs. correspondence (observation or "forward" operator)**

Difference between obs. (O) and model equivalent (F) = innovation [O-F]



Observation operator – TL/AD

- **Tangent linear & adjoint (TL/AD)**
- **Differences in determination of <u>increments</u>**



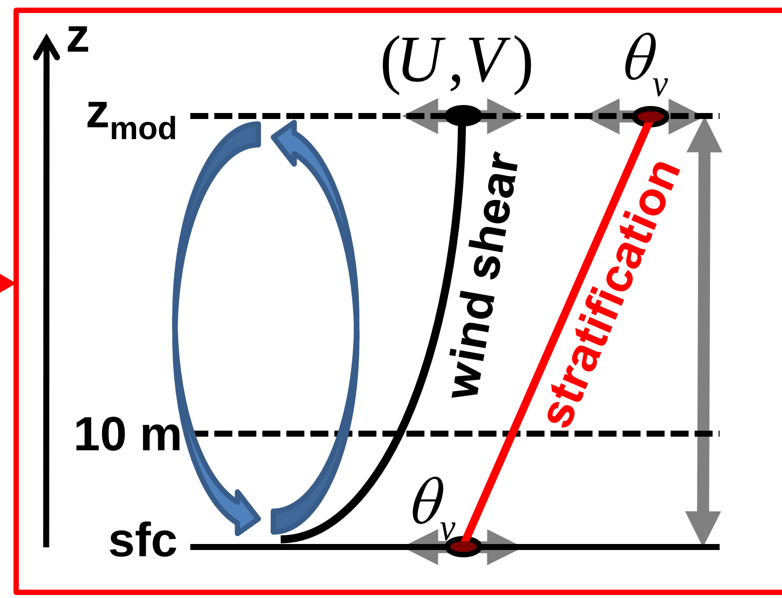
Observation operator – TL/AD

- **Control variables** of **equivalent neutral** operator:
  - Surface layer **momentum turbulent transfer (wind stress)**
  - Controlling factors represented by **Richardson number**

$$\frac{z}{L} \sim Ri_b = \frac{g}{\bar{\theta}_v}\frac{\left(\theta_{v,z_{\mathrm{mod}}} - \theta_{v,sfc}\right) z_{\mathrm{mod}}}{\left(U_{z_{\mathrm{mod}}}\right)^2 + \left(V_{z_{\mathrm{mod}}}\right)^2}$$

buoyancy vs. wind shear

  - **Control variables:**
    - **(U,V) @ Z_{mod}**
    - **θ_v @ Z_{mod}**
    - **θ_v @ surface (SST)**
    - **Z_{mod} itself**



Observation operator – TL/AD

- **“Complete” TL** of operator
- **Equivalent neutral** wind **perturbations**:

$$\delta U_{EN}(10m) = \left(\frac{\partial U_{EN}}{\partial U_{mod}}\right)\delta U_{mod} + \left(\frac{\partial U_{EN}}{\partial V_{mod}}\right)\delta V_{mod} + \left(\frac{\partial U_{EN}}{\partial Z_{mod}}\right)\delta Z_{mod} + \left(\frac{\partial U_{EN}}{\partial \theta_{v,mod}}\right)\delta\theta_{v,mod} + \left(\frac{\partial U_{EN}}{\partial \theta_{v,sfc}}\right)\delta\theta_{v,sfc}$$

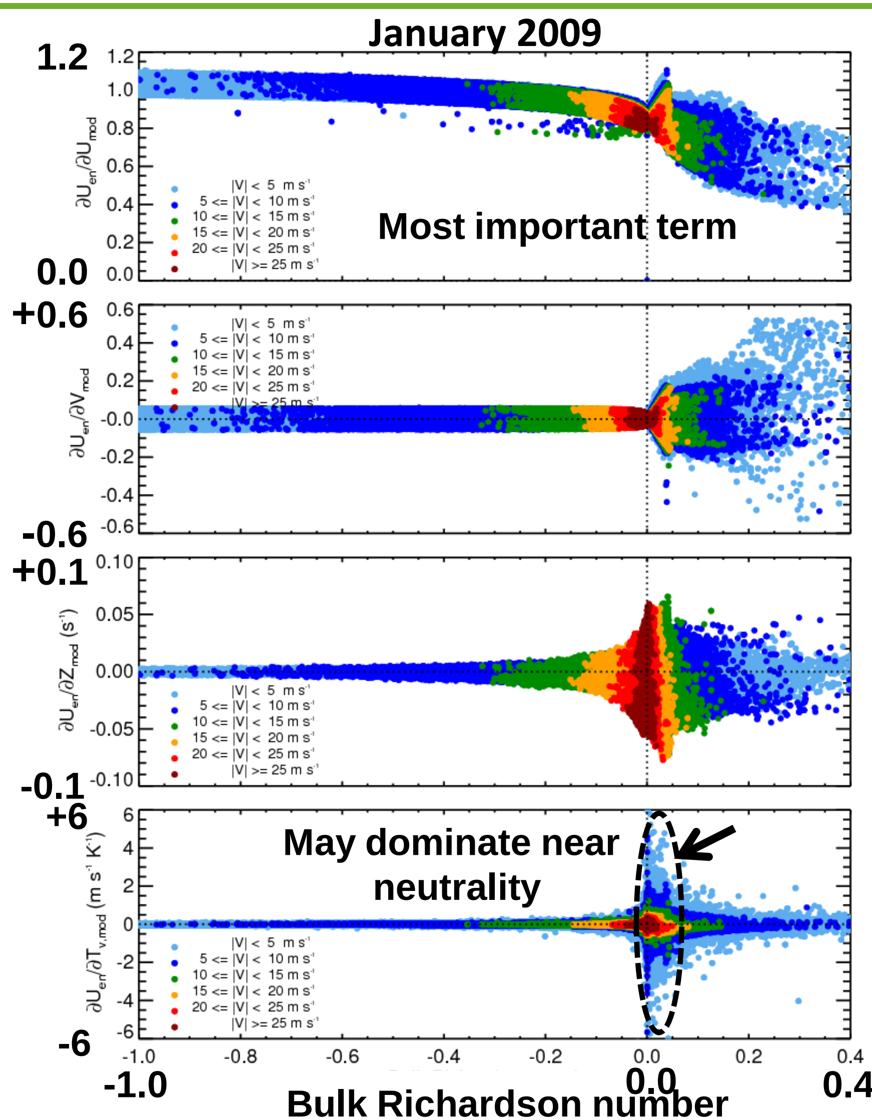
$$\delta V_{EN}(10m) = \left(\frac{\partial V_{EN}}{\partial U_{mod}}\right)\delta U_{mod} + \left(\frac{\partial V_{EN}}{\partial V_{mod}}\right)\delta V_{mod} + \left(\frac{\partial V_{EN}}{\partial Z_{mod}}\right)\delta Z_{mod} + \left(\frac{\partial V_{EN}}{\partial \theta_{v,mod}}\right)\delta\theta_{v,mod} + \left(\frac{\partial V_{EN}}{\partial \theta_{v,sfc}}\right)\delta\theta_{v,sfc}$$

$\left(\frac{\partial X_{EN}}{\partial Y_{mod}}\right)$ **Jacobian** estimated w/ finite differences of **NL (forward) operator** output obtained by individually perturbing control variables (**perturbation method**)

Perturbations of 1×10^{-3} were found appropriate

Observation operator – TL/AD

- **Jacobian**



$$\left(\frac{\partial U_{EN}}{\partial U_{\mathrm{mod}}}\right)$$

$$\left(\frac{\partial U_{EN}}{\partial V_{\mathrm{mod}}}\right)$$

$$\left(\frac{\partial U_{EN}}{\partial Z_{\mathrm{mod}}}\right)$$

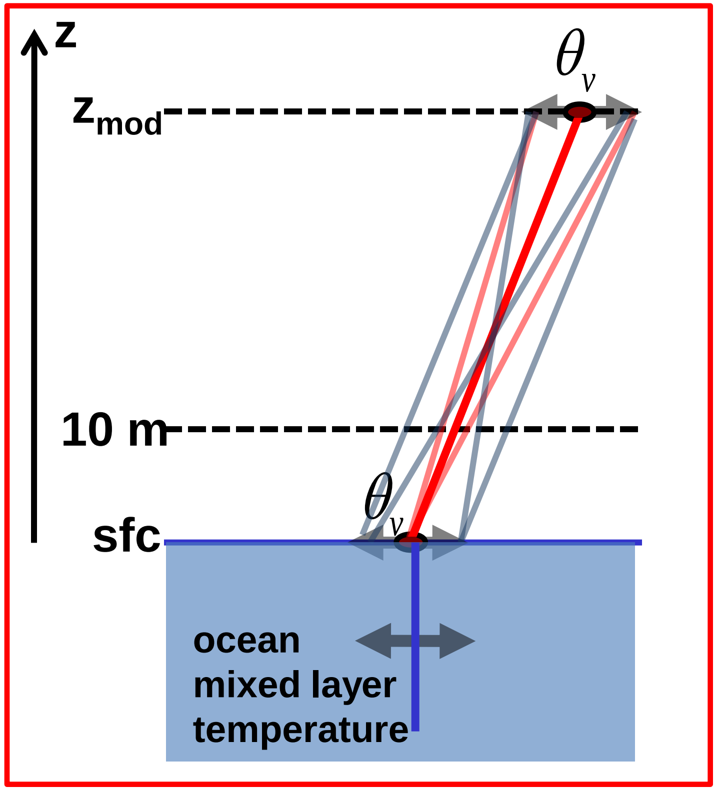
$$\left(\frac{\partial U_{EN}}{\partial \theta_{v,\mathrm{mod}}}\right) = -\left(\frac{\partial U_{EN}}{\partial \theta_{v,sfc}}\right)$$

Observation operator – TL/AD

- **Increments on θ_v desirable?**

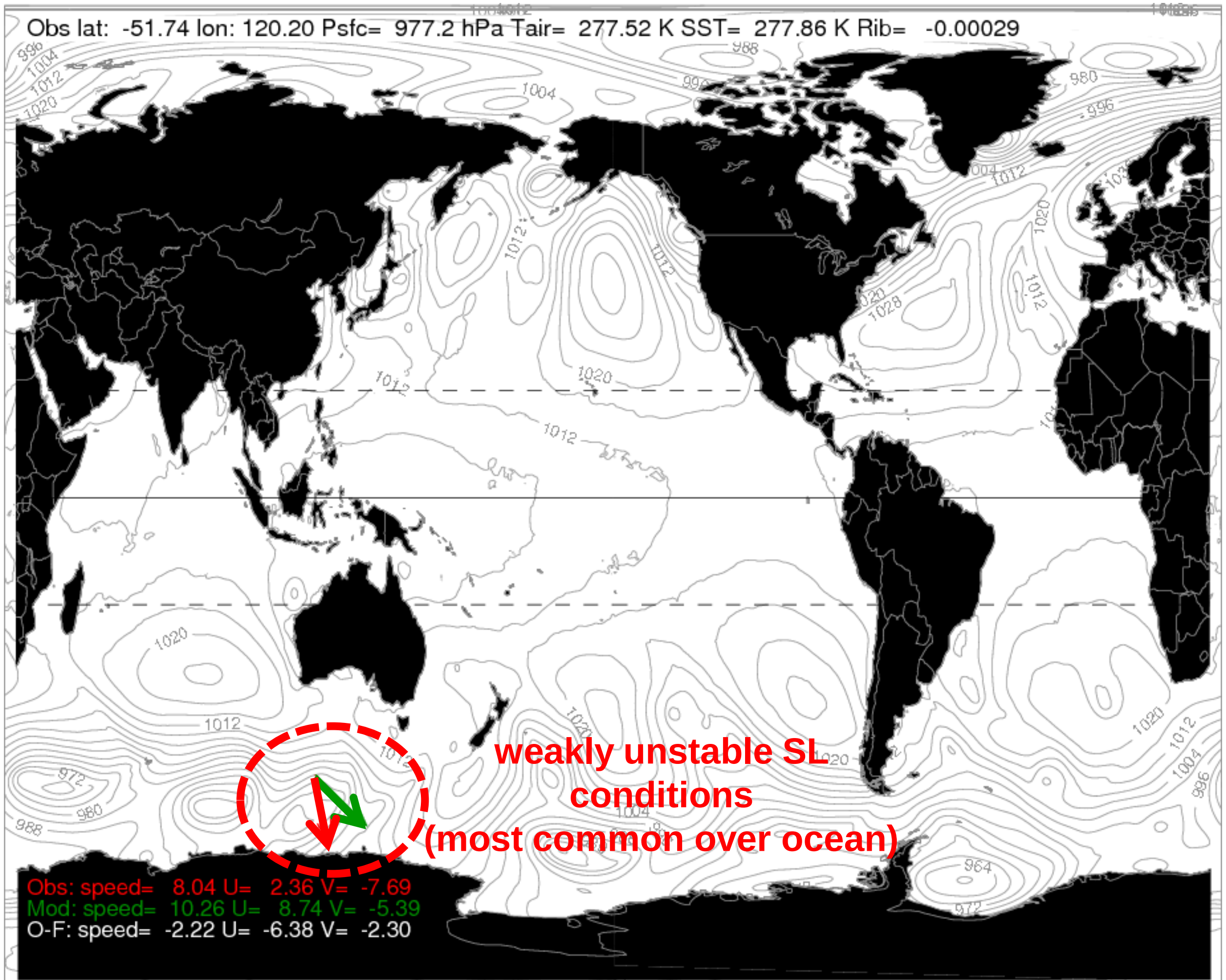
  e.g. adjusting sfc layer stratification to adjust wind toward scat. obs.

  - **Uncoupled** system
    - **SST ($\theta_{v,sfc}$) fixed** (separate analysis)
    - **Sensitivity** projected only at **upper level** (z_{mod}): **increments only on $\theta_{v,\mathrm{mod}}$**
    - **Over-constrained** problem…
  - **Coupled atmosphere-ocean** system (looking ahead…)
    - Availability of **ocean background error statistics** (on SST)
    - Allow estimation of **atmosphere-ocean covariances**
    - ➢ **Increments on SST from scat. wind obs. operator** possible …



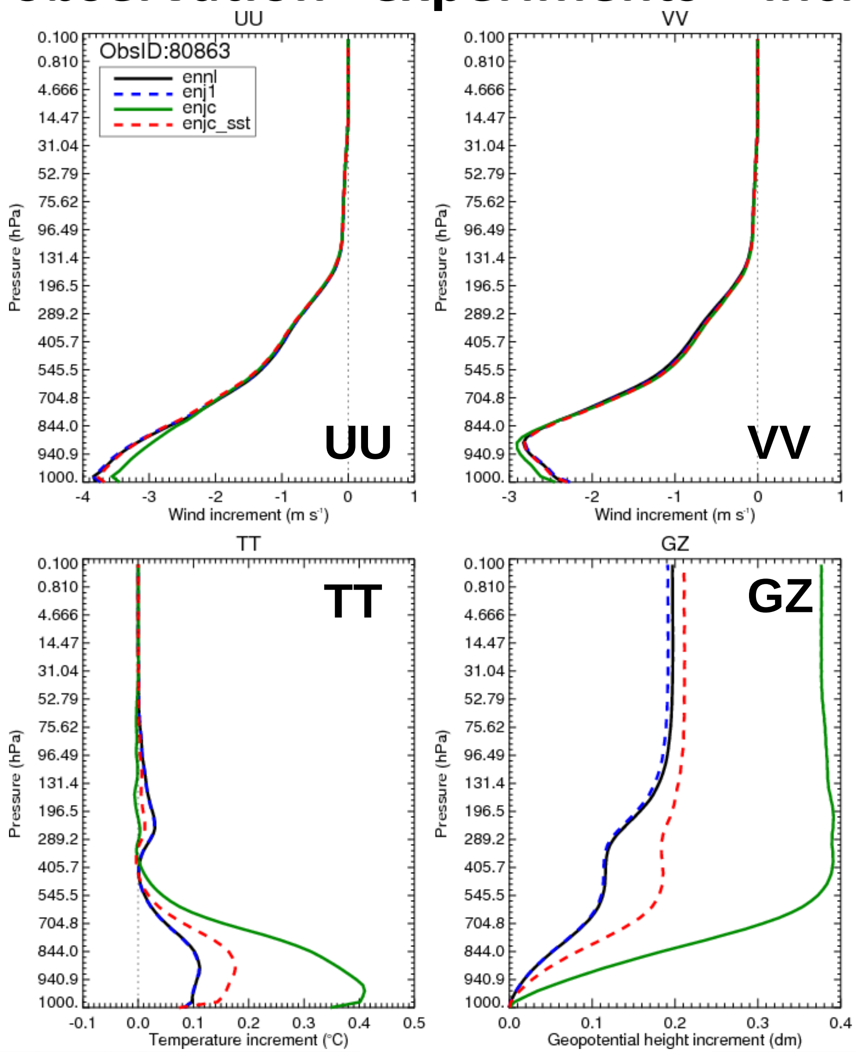
Observation operator – TL/AD

- "One observation" experiment – increment profiles



Observation operator – TL/AD

- **“One observation” experiments – increment profiles**



(interpolation + cov) (black solid line)

Sensitivity on:

- (blue dashed line) **(U,V,z_{mod})**
- (green solid line) **(U,V,z_{mod}) & $\theta_{v,\mathrm{mod}}$ only**
- (red dashed line) **(U,V,z_{mod}) & $\theta_{v,\mathrm{mod}}$ & $\theta_{v,sfc}$**

Notice upward propagation of information through error covariances from assimilation of <u>surface wind data</u>

Observation operator – TL/AD

- Proposed **TL** of operator

$$\delta U_{EN}(10m) = \left(\frac{\partial U_{EN}}{\partial U_{\text{mod}}}\right)\delta U_{\text{mod}} + \left(\frac{\partial U_{EN}}{\partial V_{\text{mod}}}\right)\delta V_{\text{mod}} + \left(\frac{\partial U_{EN}}{\partial Z_{\text{mod}}}\right)\delta Z_{\text{mod}} + \left(\frac{\partial U_{EN}}{\partial \theta_{v,\text{mod}}}\right)\delta\theta_{v,\text{mod}} + \left(\frac{\partial U_{EN}}{\partial \theta_{v,sfc}}\right)\delta\theta_{v,sfc}$$

$$\delta V_{EN}(10m) = \left(\frac{\partial V_{EN}}{\partial U_{\text{mod}}}\right)\delta U_{\text{mod}} + \left(\frac{\partial V_{EN}}{\partial V_{\text{mod}}}\right)\delta V_{\text{mod}} + \left(\frac{\partial V_{EN}}{\partial Z_{\text{mod}}}\right)\delta Z_{\text{mod}} + \left(\frac{\partial V_{EN}}{\partial \theta_{v,\text{mod}}}\right)\delta\theta_{v,\text{mod}} + \left(\frac{\partial V_{EN}}{\partial \theta_{v,sfc}}\right)\delta\theta_{v,sfc}$$

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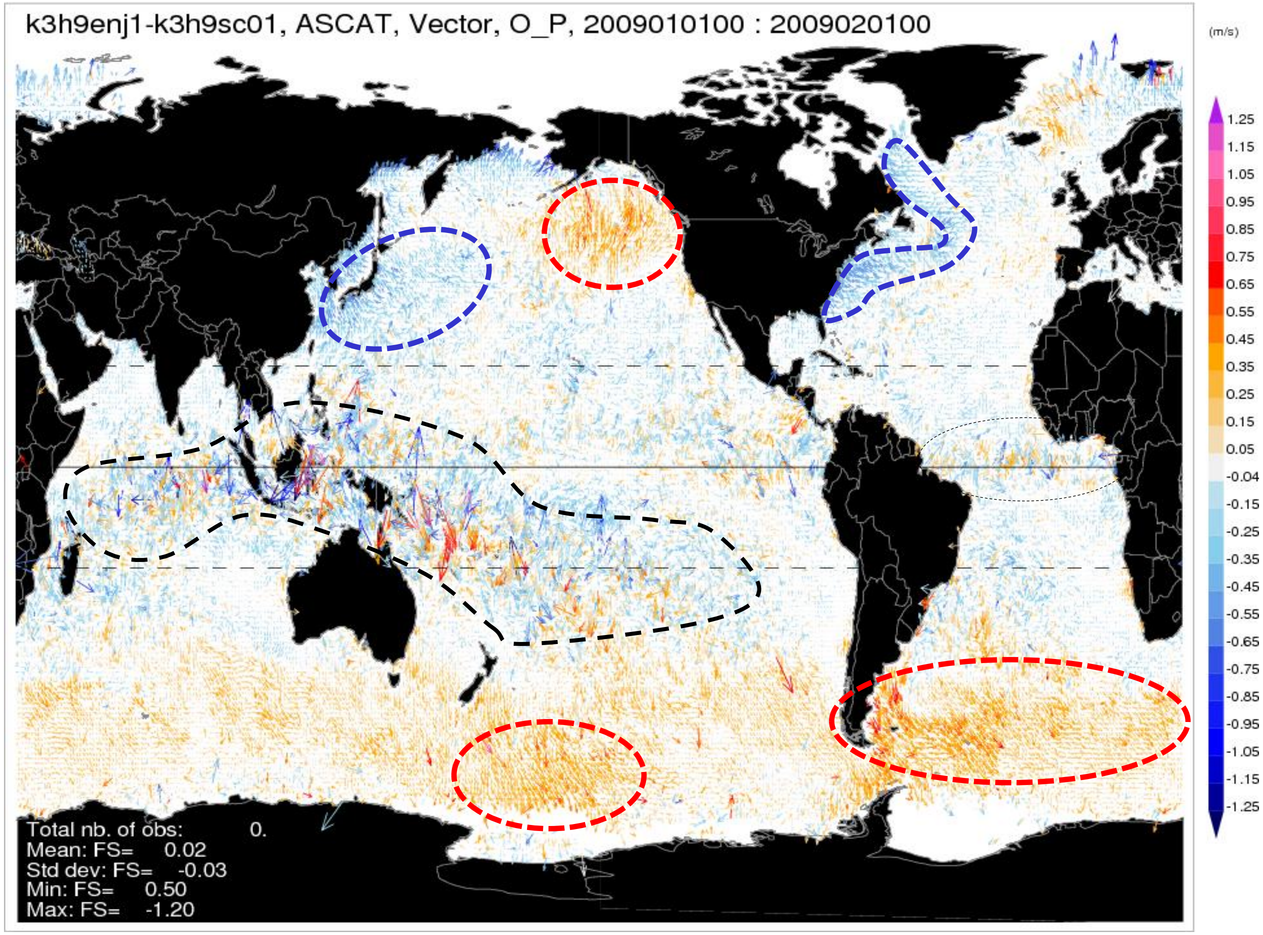
Data assimilation experiments

- **3D-var F**irst-**G**uess at **A**ppropriate **T**ime (FGAT)
  - Adequate framework for assessing impact of **obs. operator**
- « Simplified » configuration
  - Feed from QC`d observations obtained from prior control cycle (ensures use of **identical data selection as in control experiment**)
  - Background check and QC-var disabled (**faster execution**)
  - Surface analyses from prior control cycle
- **Control** cycle: Based on **currently operational** configuration
  - Operational surface layer operator (interpolation of gridded 10m diagnostics)
  - Variational system v10.2.2, GEM v3.2.2
  - Assimilated: RAOBs, aircraft, profilers, satwinds, ATOVS, GOES, GPS-RO, in situ surface, **SeaWinds & ASCAT** scatterometer winds
- **Experiment**: Introduction of **new surface obs. operator** (for scatterometer equivalent neutral winds)
- **Test period**: January 2009

Observation operator – impact (innovation)

- **Average differences in [O-F] over January 2009**

$$[O\text{-}F_{equiv.\ neutral}] - [(O\text{-}0.2ms^{-1}) - F_{real}]$$



Average difference ≈ 0

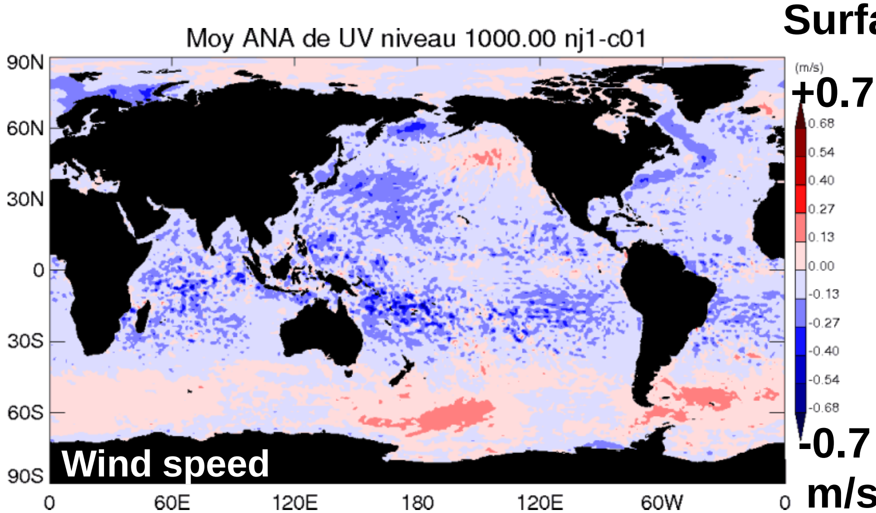
Significant regional differences
↓
function of surface layer stability & wind speed

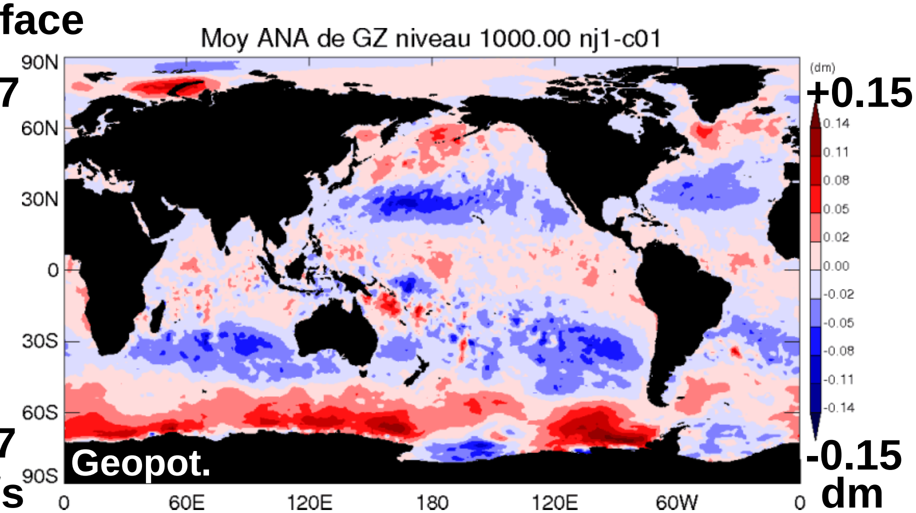
Observation operator – impact (analyses)

- **Impact on 3D-var analyses (mean differences over Jan. 2009)**

difference = (new operator - control)

Surface



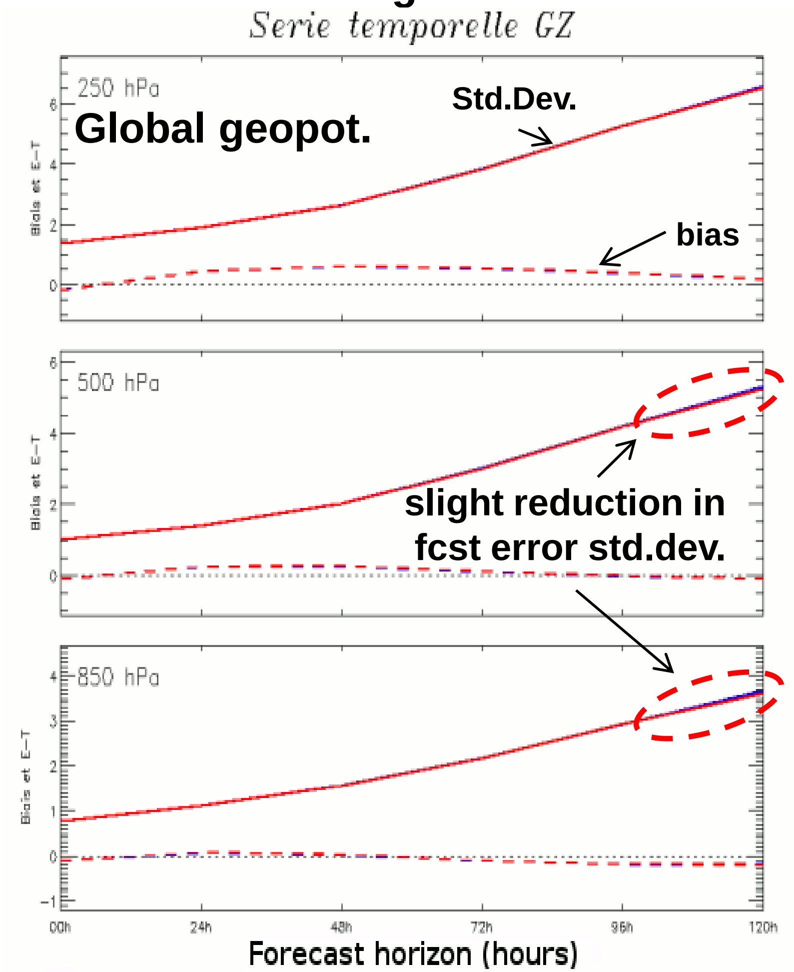


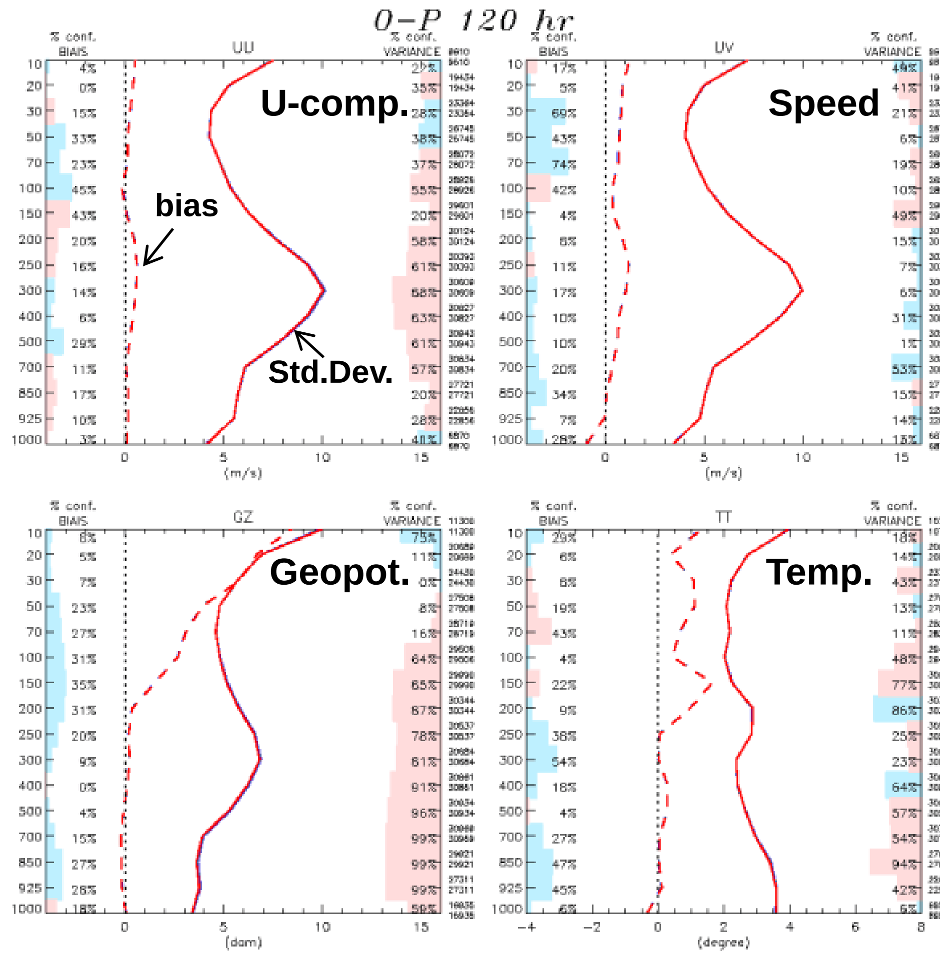
Observation operator – impact (forecasts)

- **Impact on forecasts**

  Verification against radiosondes

Control
Equivalent neutral obs. operator





Global 5-day forecasts

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Part 4

Characterizing innovations
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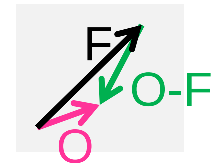
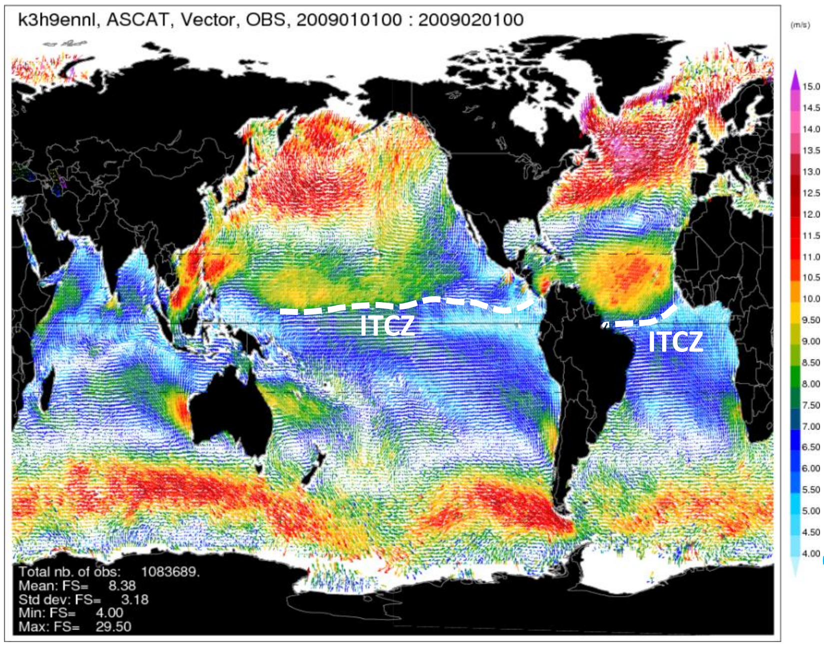
Model short-term forecasts vs. scatterometer observations

Model short-term forecasts vs observations

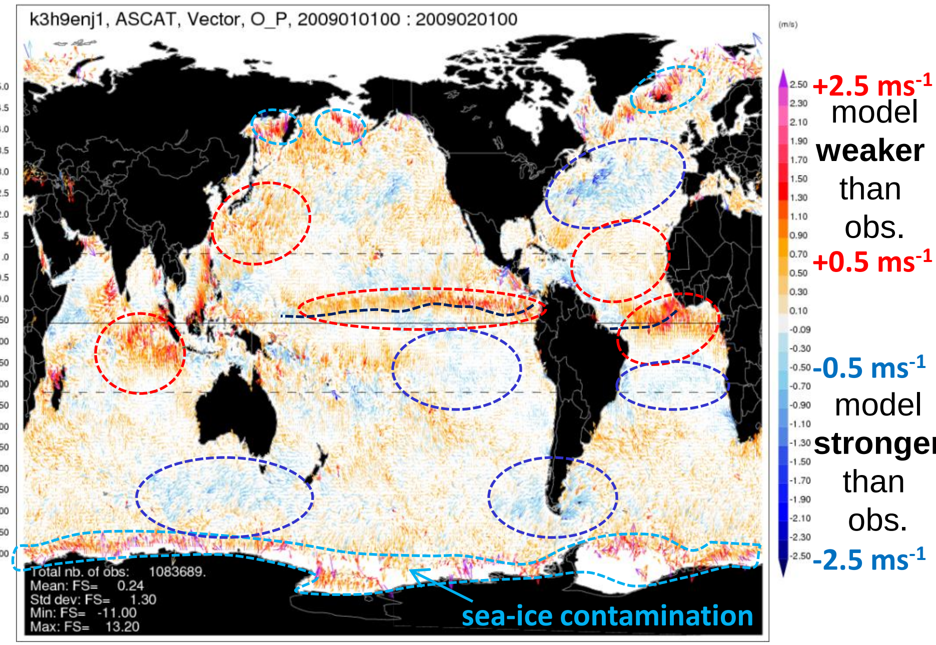
- **ASCAT (Jan. 2009 mean over 1°x1° grid)**



Observed wind vectors



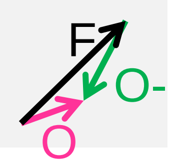
[O-F] wind vectors



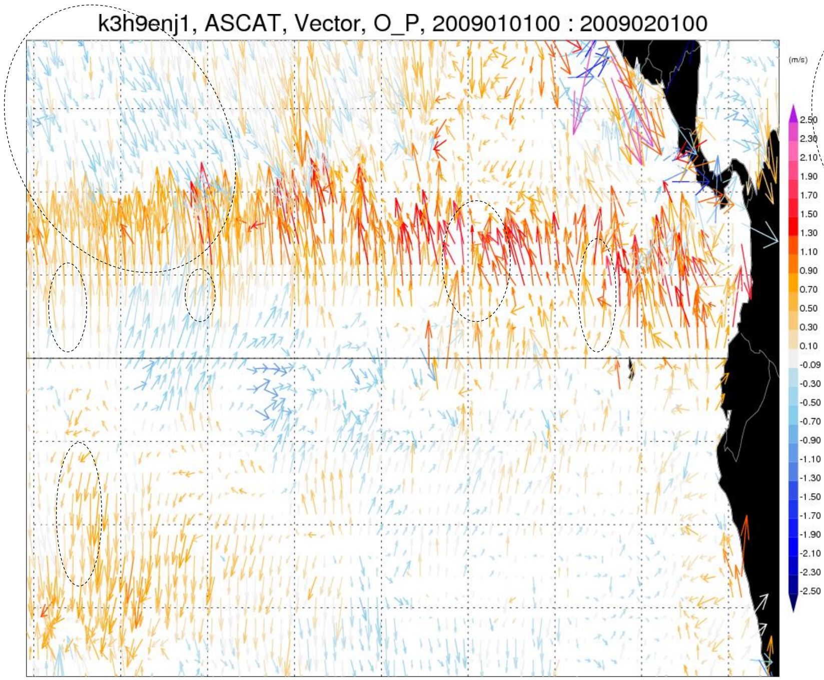
- Model equiv. neutral winds too strong over **Gulf Stream** & zone between **Atlantic sub-tropical high** and **storm track**
- Model equiv. neutral winds **too strong** in **wind max**. in **SH storm track**
- Equiv. neutral winds **too weak** over **Kuroshio**
- Equiv. neutral winds **too weak** around **Atlantic sub-tropical high**, but **too strong** in **SH trade winds** (Atlantic and E. Pacific)
- **Meridional** equiv. neutral winds **too weak** around **ITCZ** + **tropical Indian Ocean**

Model short-term forecasts vs observations

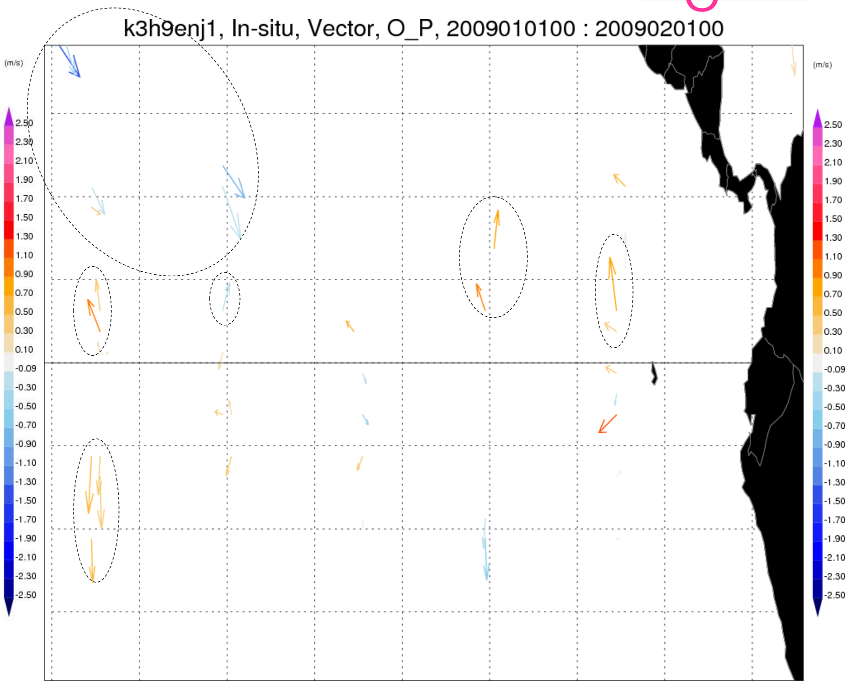
- **Equatorial eastern Pacific [O-F] wind vectors**



ASCAT



TAO buoys



+2.5 ms^{-1} model **weaker** than obs. +0.5 ms^{-1}

-0.5 ms^{-1} model **stronger** than obs. -2.5 ms^{-1}

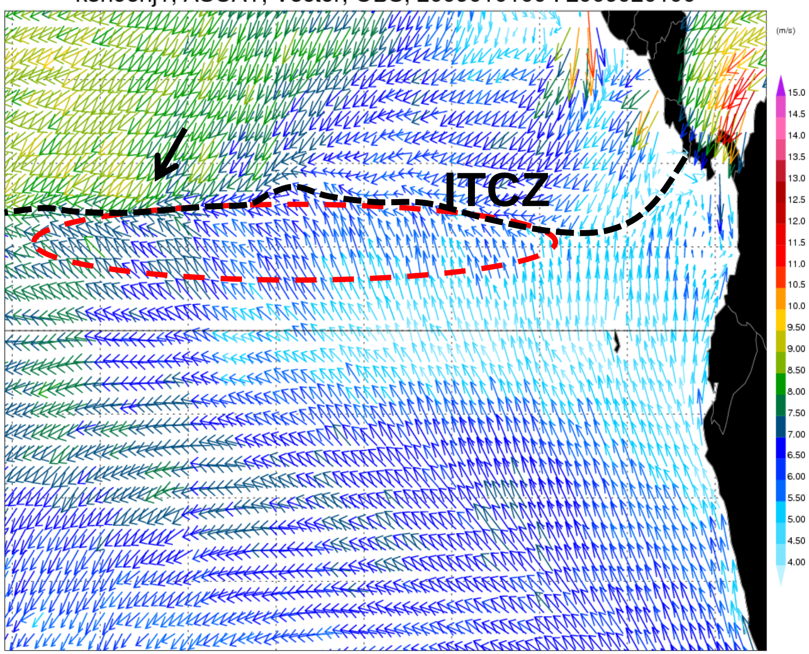
Short-term forecast errors w.r.t. scatterometer retrievals
confirmed
by comparison with in-situ obs.

Model short-term forecasts vs observations

- **Equatorial eastern Pacific obs vs. model (monthly average)**

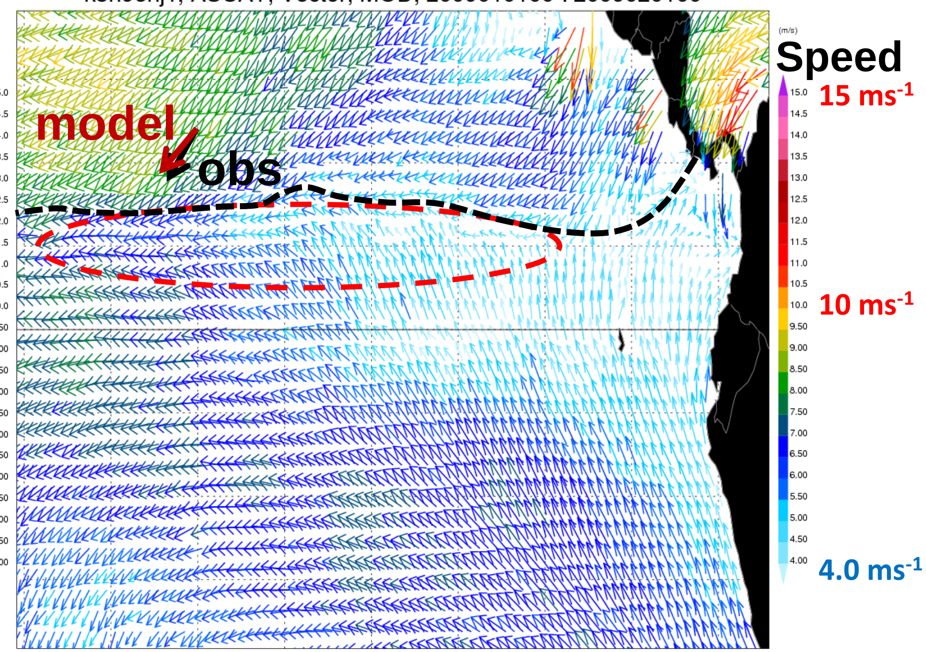
ASCAT obs.

k3h9enj1, ASCAT, Vector, OBS, 2009010100 : 2009020100



Model 6hr fcsts

k3h9enj1, ASCAT, Vector, MOD, 2009010100 : 2009020100



Persistent weaker convergence around ITCZ

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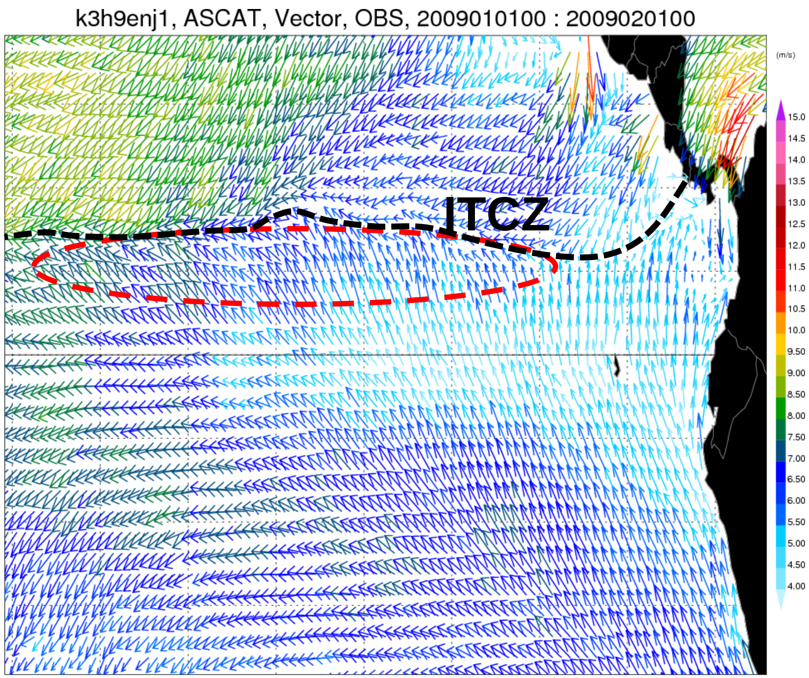
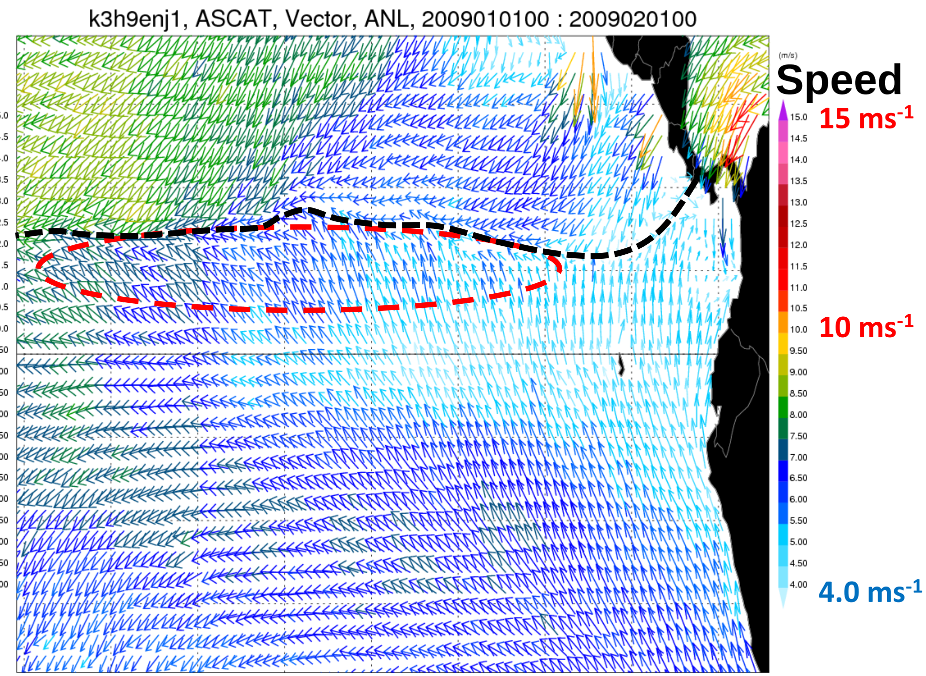
Model short-term forecasts vs observations

- **Equatorial eastern Pacific obs vs. model**

ASCAT obs.



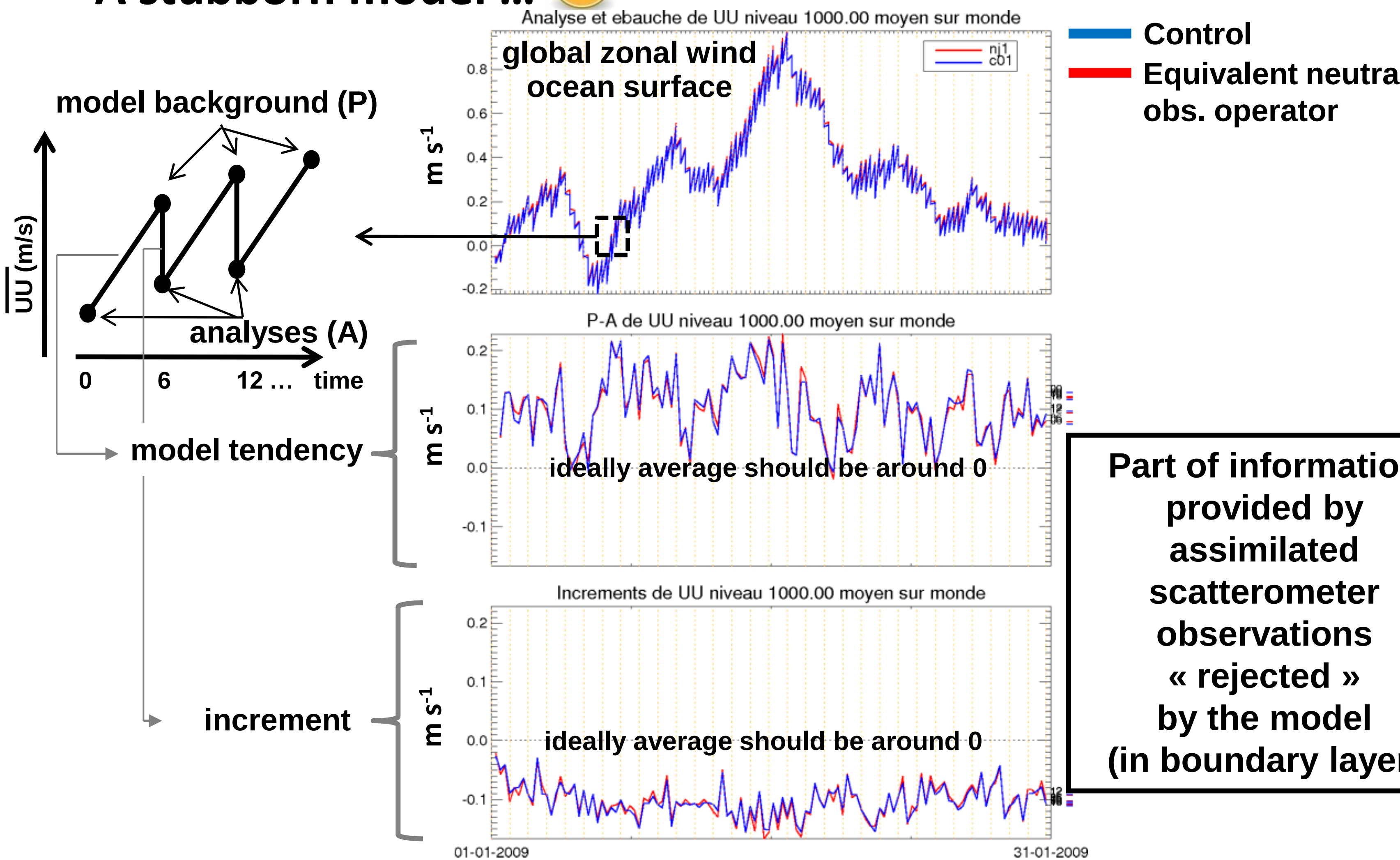
Analyses



Better representation of convergence around ITCZ in analyses
(from assimilation of scat. winds!)
But **persistent errors** in **model background** indicate that **information** provided by scat. winds partially **rejected** during subsequent 6-hr forecasts

Data assimilation vs. model

- **A stubborn model …**



Part of information provided by assimilated scatterometer observations « rejected » by the model (in boundary layer)

Summary

- New observation operator for:
  - Better representation of fundamental character of scat. observations (**improved innovations**)
  - **Increments** determined from representation of **turbulent transfer sensitivities** (TL/AD based on surface layer physics)
- Impact:
  - Noticeable changes to **analyses**
  - Has **slight positive impact** on **medium-range forecasts**
  - **Neutral** for **shorter-range forecasts**

  - But also: provides for **more accurate view** on **background (model) errors** in **surface wind stress** over **global ocean**

↳ **Possible diagnostic to characterize boundary layer model errors**

Concluding remarks

- Model vs. scatterometer observations
  - Distinct **signals** in model **background errors** over well-defined **large areas**. Most notably :
    - Model winds appear **too strong in extra-tropical storm tracks** (particularly in the unstable boundary layer over Gulf Stream)
    - **Lack of convergence around ITCZ** in E. Pacific & Atlantic

- Assimilation of boundary layer observations … a problem?
  - Information introduced in boundary layer by assimilation of scat. winds partially "rejected" during subsequent model short-term forecasts
  - This needs further attention to improve **model-obs. synergy**

Des questions?