Space Weather: Observational evidence for coupling and feedbacks involving the ITM

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The Sun & Earth form a complex system which has characteristic properties

✓ Prediction is difficult based on knowledge of components alone

“The whole is greater than the sum of the parts “
The Sun & Earth form a complex system which has characteristic properties

✓ Prediction is difficult based on knowledge of components alone
✓ History matters

“Butterfly Effect”

The Sun & Earth form a complex system which has characteristic properties

- Prediction is difficult based on knowledge of components alone
- History matters
- Emergent features

“Science of Surprise”

Still from “The Mummy”
The Sun & Earth form a complex system which has characteristic properties

- Prediction is difficult based on knowledge of components alone
- History matters
- Emergent features
- Negative and positive feedbacks

“Simple cause & effect are rare.”
The Sun & Earth form a complex system which has characteristic properties.

Interactions between components define behavior
Not contained in the individual pieces
Break into smaller digestible pieces -- lose behavior
Close-Up on the Upper Atmosphere
Remember what we are dealing with ….
Evidence for Active ITM Influences throughout Geospace

Four coupling pathways:

- Mass & momentum outflows
- Solar wind energy inflow
- Active electrodynamic interactions
- Reactive species: production & transport

Fundamental physics:
Ion-neutral coupling
Cross-scale coupling
Chemical-dynamical coupling
Evidence for Active ITM Influences throughout Geospace

Four coupling pathways:

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Outflows best correlated with solar wind Pdyn fluctuations: Reason Unknown [c.f. Fok et al., 2005]

Outflows

Outflow: Acceleration to > escape velocity

Upwelling: Increase in scale height

After Strangeway et al., [2005] as summarized in Moore and Horwitz, 2007 and Lotko, 2007
Accumulating evidence that most of the mass, momentum, and energy coupling occurs on relatively small spatial scales.

Schunk, GEM tutorial, 2006
**Mass and Momentum Outflow**

Sondrestrom view of polar cap patch ions energized in nightside auroral zone. Adapted from Semeter et al. 2003 in Lotko 2007 review.

Structured ion outflow creates structured neutral outflow through charge exchange.

Adapted from Gardner & Schunk, 2005.
Mass and Momentum Outflow

Solar wind - energy inflow

Structured energy inputs (Poynting flux, Joule heating, soft precipitation) and convecting ionospheric density structures

Structured Neutral & Ion Outflows

- Effects plasma waves, ring current & rad belt composition, charge exchange losses & atmospheric loss
- Patchy plasma sheet composition. Variable oxygen geocorona
- Charge exchange & O backsplash from H/H+ auroras creates neutral O outflows
- Cause structured “upwelling” of ions, polar wind jets, neutral holes
- Further acceleration by waves and field-aligned potentials at high altitude cause oxygen outflows

Lotko [2007], Sojka and Schunk references
Oxygen ions dominate the magnetospheric plasma during extreme events in the inner region. Patchy composition.

$O^+$ can dominate even for more moderate solar and magnetic activity levels. Variability due to multiple drivers. [Greenspan & Hamilton, JGR, 2002]
LENAs sees at least 2 neutral O populations under all conditions:

- A neutral hot O geocorona
- A higher energy upflowing O population originating from the auroral zone. Possibly due to backsplash O from H/H+ auroral precipitation [Shematovich, et al., 2006]

These upward O fluxes increase in intensity with increasing magnetic activity to a few x 10^9 cm^-2s^-1.

Wilson et al., 2003; 2005
Suggested positive feedbacks on magnetotail stability

- Ionospheric outflow from auroral activity feeds O\(^+\) into magnetotail
- Produces more frequent and/or more intense auroral activity
- Increased demand for episodic unloading of tail flux
- Mass loads convection in magnetosphere, slows reconnection rate
- Less O\(^+\) in dayside plasma sheet implies faster dayside merging
- Slower nightside reconnection rate cannot balance the dayside rate

Saturation of the polar cap potential breaks positive feedback loop. Lotko, 2007
Consequences (review Moore & Horwitz, 2007): (1) reduces Alfven speed of inflow to the dayside reconnection region, (2) slows reconnection, (3) reduces convection

Observed occurrence rate of cold convecting ions at the dayside magnetosphere for northward (left) and southward (right) IMF [Chen and Moore 2006].
Evidence mass-loading by drainage plume slows reconnection

Sign of weakened coupling to the solar wind & evidence for decreased reconnection rate.

Extension of ionospheric plasma into the inner magnetosphere

Important component of mass circulation not included in MHD models

~10% effect for Ne < 10 cm⁻³ plumes. However, Ne can reach 100 cm⁻³

Borovsky & Denton, 2006
ITM Mass Loading of Magnetospheric Convection

Solar Wind Electric Field

Reduces reconnection rate, $\Phi_{pc}$, & outflows

Mass-loading slows convection

Increases $\Phi_{pc}$, enhances convection

Greater centrifugal acceleration of upflows

More ionospheric outflow

Mass Loading of Convection

Higher O+ content of plasmasheet

Model result: Winglee et al., 2002, as summarized by Lotko, 2007
As mass-loading increases in multi-fluid model, the convection potential drops toward values predicted by AMIE model based on magnetometer data [Winglee et al., 2002]
Summary

• ITM is an active participant in Geospace system. Not just a boundary condition.
• Growing evidence that mass & momentum flows and electrodynamic parameters are all structured by the ITM.
• Coupling occurs on small spatial & temporal scales.
• Structured ion outflows produce structured neutral outflows.
• Coupling involves a broad range of scales, fluid & kinetic processes & varies in complicated ways with solar wind drivers.
• Fundamental questions in the magnetosphere and middle atmosphere cannot be answered without a more complete knowledge of ITM processes.
Highest priority ITM problems related to Geospace system science

• Understand how fundamental ITM processes work so we can recognize their signatures at the system level

• New ways of observing global patterns of energy inputs, basic state parameters, and electrodynamic quantities. Climatologies are not sufficient.

• Determine what spatial and temporal scales are needed

• Tackle the challenges & take the steps that will lead to a revolution in our understanding of geospace as a tightly coupled system of systems
Future Measurement Requirements

- Multi-point observations connecting solar driving to auroral field-aligned transport
- Connection between ionospheric (also plasmaspheric) structures, transport & outflows.
- Ion - neutral interactions
- NOx in the polar night. Quantities related to transport
- ITM Complex System: Instantaneous global patterns of energy inputs and electrodynamic parameters.