Direct Forcing of the Thermosphere-Ionosphere by Small-Scale Gravity Waves of Lower Atmospheric Origin

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Overview

1. Science: Atmospheric Coupling, Waves, & General Circulation Models
2. Gravity Wave Effects on the Upper Atmosphere
3. Possible effects on the ionosphere
4. Summary & Conclusions
5. Open science questions

Overarching science goal: coupling from below

Science goal

Investigate gravity wave-induced coupling mechanisms in
Earth's whole atmosphere
in order to advance the knowledge of
atmospheric general circulation

Technique

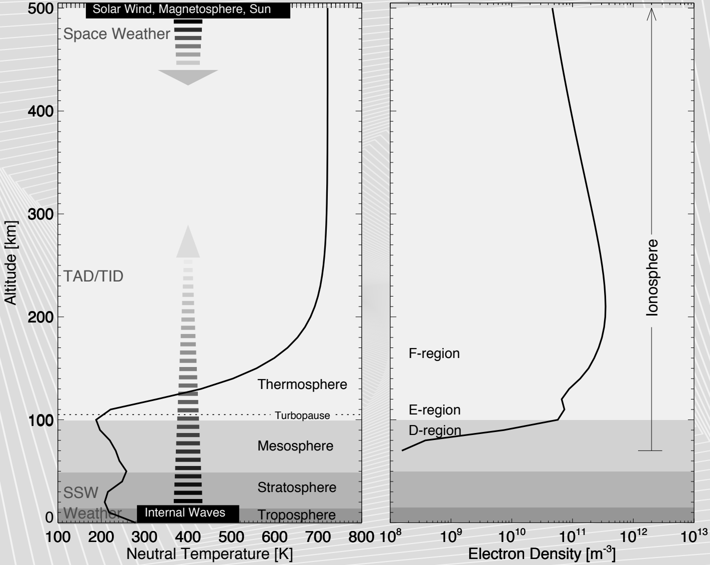
General Circulation Modeling ($\Leftarrow$ Gravity wave parameterization)

$\Downarrow$

Upper atmosphere

Determine the dynamical and thermal effects of GWs

Vertical coupling on Earth



Earth's atmosphere-ionosphere (Yiğit and Medvedev 2015, Figure 1)

Vertical coupling: Meteorological effects

LOWER ATMOSPHERE

Weather/Wave sources

$\rightarrow$ Spectrum of waves

Vertical coupling: Meteorological effects

MIDDLE ATMOSPHERE — Wave-flow interactions

LOWER ATMOSPHERE — Weather/Wave sources

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Vertical coupling: Meteorological effects

UPPER ATMOSPHERE
(THERMOSPHERE-IONOSPHERE)

(COMMUNICATION, PLANETARY MISSIONS, SATELLITE ORBITS, SPACE TRAVEL)

Significant wave-flow interactions

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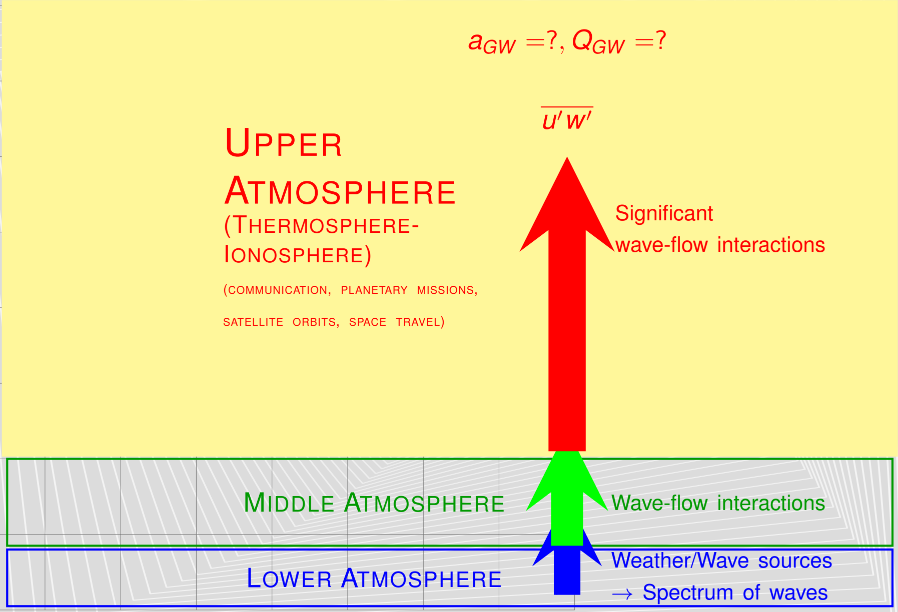
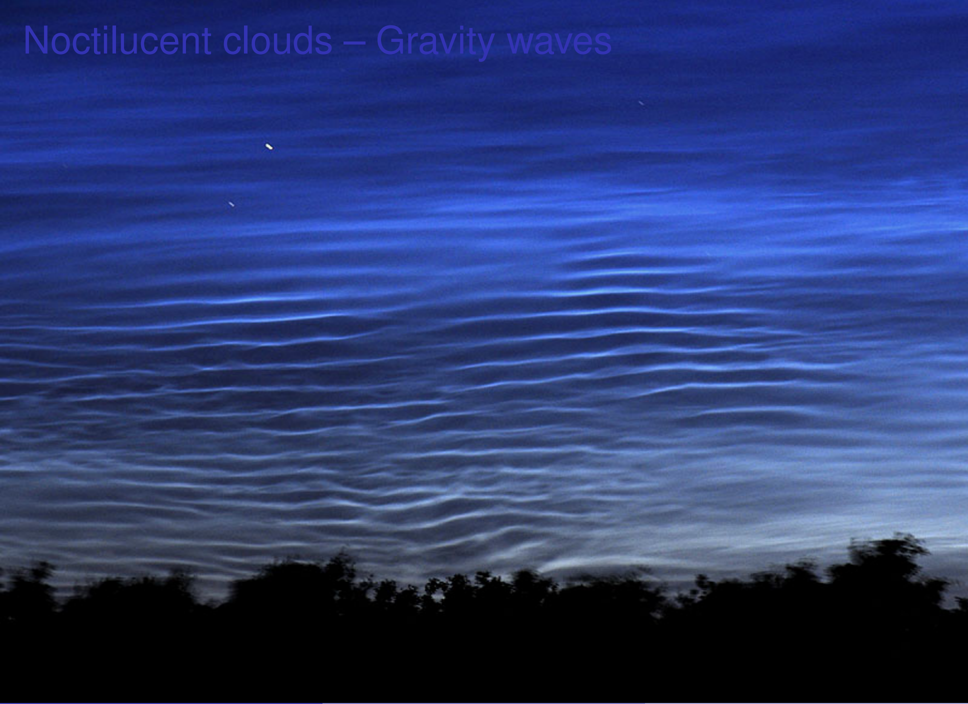


Gravity waves

Noctilucent clouds – Gravity waves



What are internal gravity waves?

Gravity waves (GWs)

- Buoyancy oscillations
- Primary generation in the lower atmosphere
- Propagate upward, interacting continuously with the atmospheric flow, e.g., via nonlinearity and viscosity

Small-scale GWs

- Important for the general circulation of the whole atmosphere system
- Challenge: unresolved & **parameterized** in general circulation models (GCMs)
- Small-scale $\Leftrightarrow$ large-scale

Gravity wave parameterizations

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Dynamical equations

$$\frac{\partial \mathbf{u}}{\partial t} = \overbrace{-\frac{1}{\rho}\nabla p - (\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla(\nu\nabla\cdot\mathbf{u}) - 2\boldsymbol{\Omega}\times\mathbf{u} + \mathbf{g} - \nu_{ni}(\mathbf{u}-\mathbf{v}_i)}^{\mathbf{a}_{res}} \quad (1)$$

Erdal Yiğit 11/19/2013

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&\quad + \mathbf{a}_{gw}\\
\frac{\partial T}{\partial t} &= Q_{res}
\end{aligned}
$$

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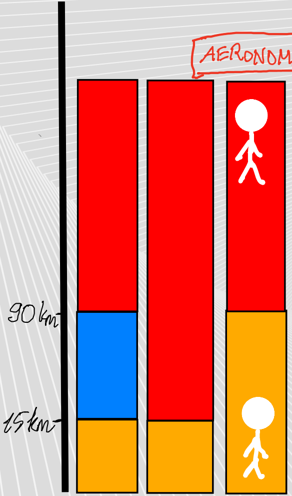
$$

$$
\frac{\partial T}{\partial t} = Q_{res} + Q_{gw} \quad (2)
$$

Erdal Yiğit 11/19/2013

Gravity Wave Effects in the Atmosphere – Year 2008



AERONOMIST

"Gravity waves are generated at high-latitudes and propagate equatorward. Lower atmospheric small-scale GWs are negligible, as they are small perturbations"

GWs get dissipated anyway before they reach the thermosphere

METEOROLOGIST

Q Who is right?

A whole atmosphere parameterization

GW whole atmosphere effects

So, how do we get a physics-based representation of the GW contributions $\mathbf{a}_{gw}$ and Q_{gw} to the energy and momentum balance in the whole atmosphere?

A whole atmosphere parameterization

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D19106, doi:10.1029/2008JD010135, 2008

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Parameterization of the effects of vertically propagating gravity waves for thermosphere general circulation models: Sensitivity study

Erdal Yiğit,[1] Alan D. Aylward,[1] and Alexander S. Medvedev[2]

Received 16 March 2008; revised 8 July 2008; accepted 22 July 2008; published 8 October 2008.

[1] A parameterization of gravity wave (GW) drag, suitable for implementation into general circulation models (GCMs) extending into the thermosphere is presented.

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- "Extended parameterization" (Yiğit and Medvedev 2013)
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- **Input**: Initial gravity wave activity at a given source level (e.g., $\sim$15 km)

Gravity wave propagation & dissipation

$$\begin{aligned} \overline{u' w_i'}(z) &= \overline{u' w_i'}(z_0)\, \rho(z_0)\rho^{-1}(z)\, \tau_i(z) \\ \beta(z) &= \beta_{non} + \beta_{ion} + \end{aligned} \tag{3}$$

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Output

GW induced dynamical ($\mathbf{a}_{gw}$) and thermal effects (Q_{gw})

Modeling framework: GCM + paramaterization

GCM

A General Circulation Model that extends into the thermosphere (Coupled Middle Atmosphere Thermosphere Model-2)

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GW representation

A GW parameterization that accounts for GW thermospheric dissipation
(Spectral nonlinear GW parameterization (Yiğit et al. 2008))

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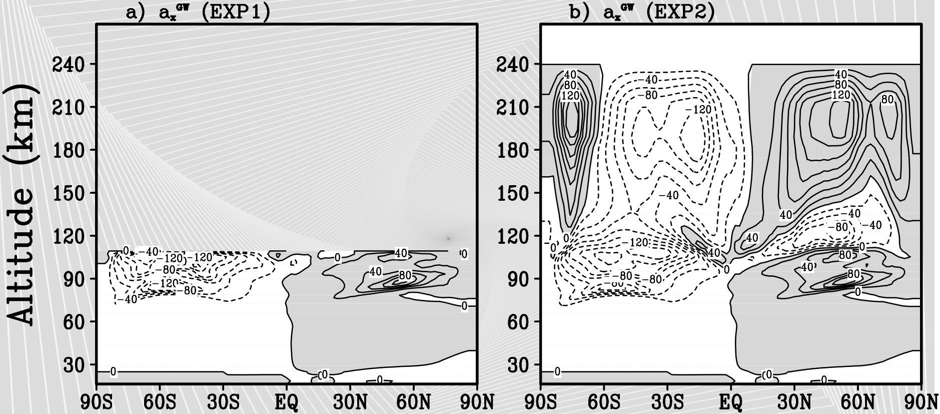
$\Downarrow$

GW effects in the thermosphere-ionosphere

Gravity wave effects in Earth's atmosphere

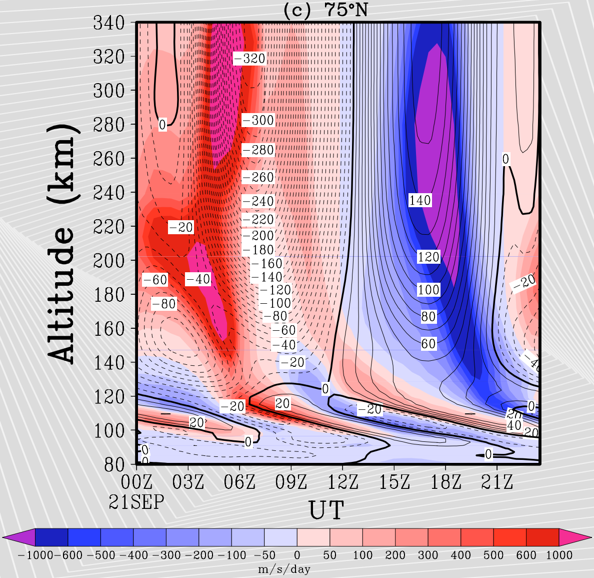
No GW effects in the upper atmosphere (OLD SCHOOL)

GWs effects **extending** into the upper atmosphere



Simulated mean GW effects with the Coupled Middle Atmosphere Thermosphere Model-2 ((CMAT2), Yiğit 2009) implementing the Yiğit et al. 2008 GW parameterization (Yiğit et al. 2009, Figure 3)

Gravity wave effects in Earth's upper atmosphere



Simulated ū (contours) and GW drag (color) (Yiğit et al. 2012, Figure 6)

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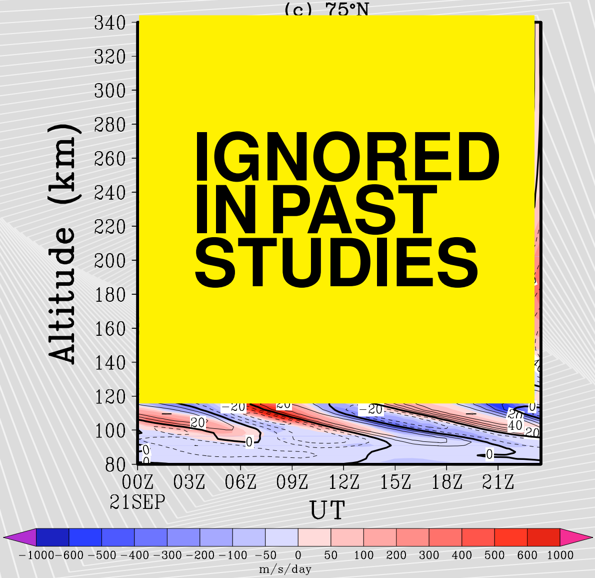

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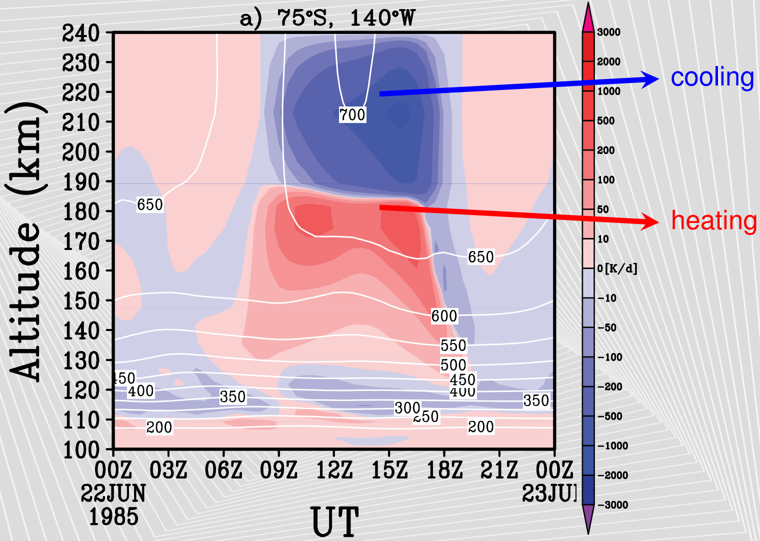
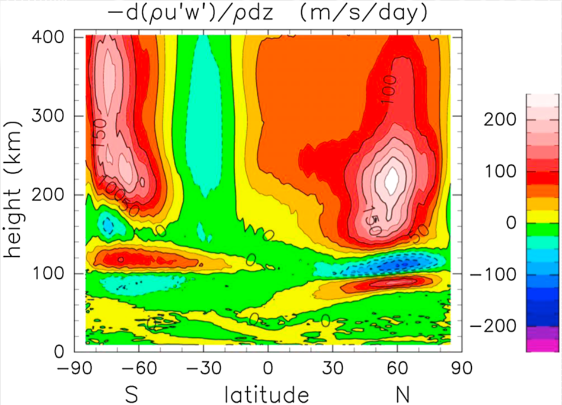
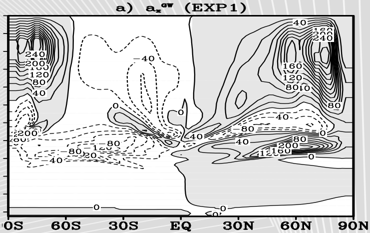
GW heating/cooling in Earth's upper atmosphere



Simulated GW heating/cooling (color) and temperatures (contour) (Yiğit and Medvedev 2009, Figure 3)

GW effects: parameterizations vs. high res.





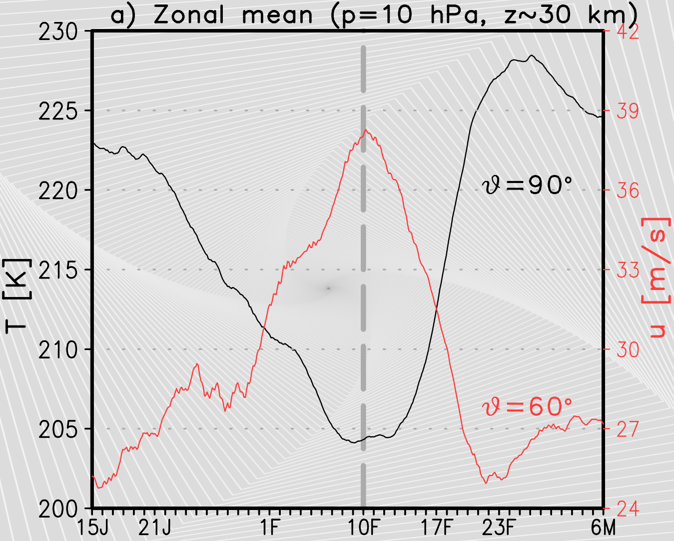
Intercomparison of parameterized GW effects (Yiğit and Medvedev 2010, Fig 10a) with high-resolution simulations of Miyoshi et al. 2014, Fig 3

GW propagation during SSWs

Science question

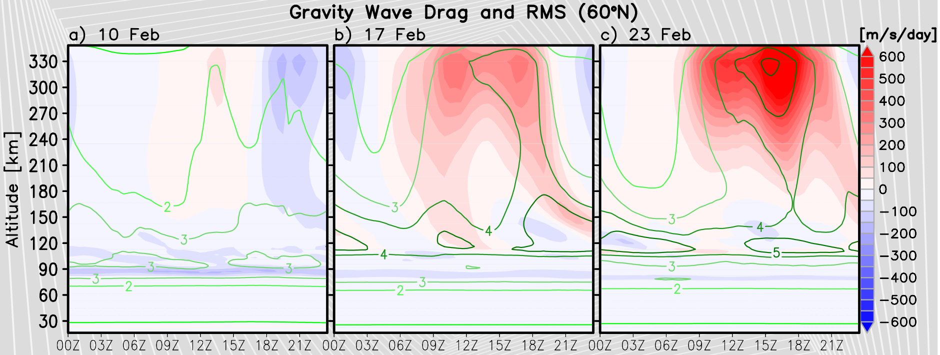
What is the role of gravity waves
in the vertical coupling
between the lower and upper atmosphere
during sudden stratospheric warmings?

A minor SSWs



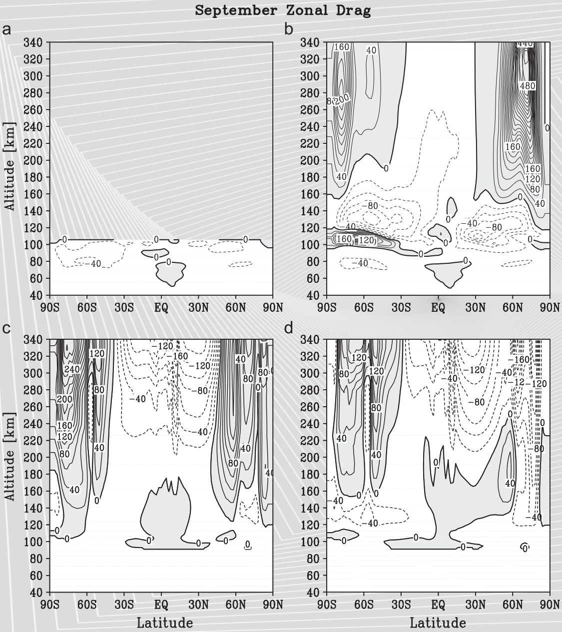
A minor SSW simulated by a GCM (Yiğit et al. 2014, Figure 1a)

GW effects during SSWs



GW propagation into the thermosphere during the different phases of the minor warming (Yiğit et al. 2014, Figure 2abc)

Ionospheric effects



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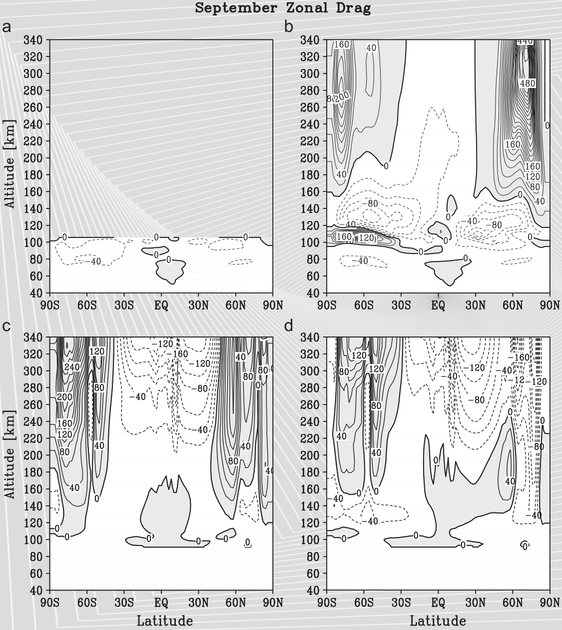

- GW dynamical effects of up to
  - $\pm$ 120 m s^{-1} day^{-1} in the lower thermosphere
  - 200 to 400 m s^{-1} day^{-1} in the high-latitude thermosphere

  are much stronger than the middle atmospheric effect of GWs, which is around 40 m s^{-1} day^{-1}.
- Thermospheric GW effects comparable to ion drag

Summary & Conclusions

Science goal

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Conclusions

- GCMs $\rightarrow$ physical insight into coupling processes (waves, storms)
- Application of a GCM implementing the Yiğit et al. 2008 scheme: powerful tool
- Gravity effects should be taken into account in the energy and momentum budget studies of the thermosphere-ionosphere system

COSPAR

COSPAR C2.2 Wave Coupling and Consequences in the Whole Atmosphere

- Moscow, 2014, MSO $\rightarrow$ NEXT: Istanbul, 2016, MSO

SCOSTEP's VarSITI Program

- Working Group Leader: Coupling by Dynamics, ROSMIC (Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate) program

Future: Some Open Science Questions

1. *What are the influences of meteorological processes in shaping the state, evolution, and variability of planetary upper atmospheres?*
2. *What is the impact of space weather on atmospheres and vertical coupling processes?*
3. *What is the significance of wave-wave interactions for atmospheric vertical coupling?*

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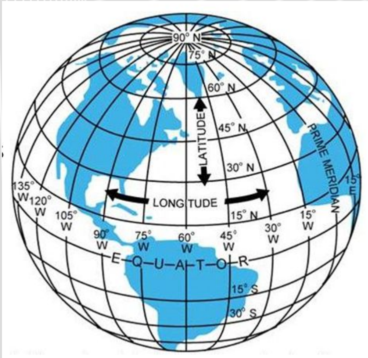
ADDITIONAL MATERIAL

General circulation modeling



- **Goal:** to predict the future state of the atmospheric circulation from knowledge of its present state by using **numerical approximations techniques** to the dynamical equations
- Solve coupled conservation equations in a global grid
- Differential equations $\rightarrow$ algebraic difference equations
- From the initial state, integrate the equations in time to get future state.